E75-68
February 26, 1968

FINAL REPORT

RADIO ASTRONOMY EXPLORER

APOGEE KICK MOTOR

CONTRACT NAS5-9336

(MAY 5, 1966 - MARCH 31, 1967)

Prepared by

THIOKOL CHEMICAL CORPORATION

ELKTON DIVISION

ELKTON, MARYLAND

FOR

GODDARD SPACE FLIGHT CENTER

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General Manager

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ABSTRACT

The object of this report is to present a history of the design, development, and demonstration testing of the Apogee Kick Motor for the Radio Astronomy Explorer Spacecraft. The program was conducted at the Elkton Division of Thiokol Chemical Corporation between May 5, 1966 and March 31, 1967. Ten motors were manufactured. The test program consisted of four sea-level firings at Thiokol, two simulated altitude tests at the Arnold Engineering Development Center, and delivery of four motors.

Based on these tests, TCC concludes that the motor will meet all of the NASA design requirements as presented in Specification 67-58, Rev A, dated September 29, 1965. These requirements and our demonstrated values are presented below:

Parameter	NASA Design Requirements	Thiokol Demonstrated Values[1]
Total Impulse, lbf-sec, 45±25°F, vac	44,500	44,471 (AEDC)
Total Impulse Standard Deviation, lb-sec	±440	+62 -111 (AEDC)
Total Weight, lbm	175 (max)	173.3
Diameter, inches	17.4 (max)	17.4
Misalignment,[2] ~~degrees,[2]~~	15 min	2.21 min

TCC considers the motor qualified for use on the R. A. E. satellite; the motor will perform successfully within the environment and within the constraints established by the above referenced NASA Specification.

[1] See Appendix A.

[2] The angle between the centroid of the nozzle and a line perpendicular to the mounting flange.

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I. DISCUSSION

A. DESIGN REQUIREMENTS

This motor was designed for use as the Apogee Kick motor on the Radio Astronomy Explorer Satellite. NASA Contract #NAS5-9336 and Specification 67-53, Rev. A, dated September 29, 1965, governed the design of the motor. The design will deliver 44,500 ± 440 lbf-sec after being exposed to a vacuum of 10^{-9} mm of Hg for 48 hours at a temperature of 45 ± 25°F. Motor-to-motor total impulse variability does not exceed the ± 440 lbf-sec specification requirement. The motor has a maximum case diameter of 17.4 inches and weighs 173.3 pounds, within the specification requirements of 17.4 inches and 175 pounds. Figure 1 shows the motor assembly.

The motors are equipped with a redundant one-amp/one-watt no-fire (1A/1W) pyrogen ignition system as required by the specification. This redundant ignition system is located at the aft end on the nozzle closure and is mounted symmetrically. The pyrogen was originally designed and qualified for space application during the NASA Gemini program.

B. DESIGN FEATURES

1. Case

The motor case, Thiokol drawing E18909, is fabricated from 6Al4V titanium alloy, hemispherical forgings. These forgings are machined to shape and welded with an electron beam at the equator. The case inside diameter is 17.318 ± 0.020 inch, with a wall thickness of 0.038 + 0.006 inch. Case wall thickness was based on a 1.5 burst/MEOP[3] safety factor.

The mounting flange is also fabricated from a machined 6Al4V titanium forging (pierced die) and welded to the aft hemisphere of the case. The ring contains 24 mounting holes and meets the specifications of NASA Drawing #1058124.

The ring is 0.090-inch thick and its outside diameter is 15.50 inches.

2. Insulation

Most of the interior surface of the case is insulated with an asbestos filled buna-N rubber material (V-44). The center of the dome section is insulated with a vitreous silica phenolic disc of MX2625. This disc prevents burn through of the head end that may result from the vortexing combustion gases.

[3]MEOP = Maximum expected operating pressure.

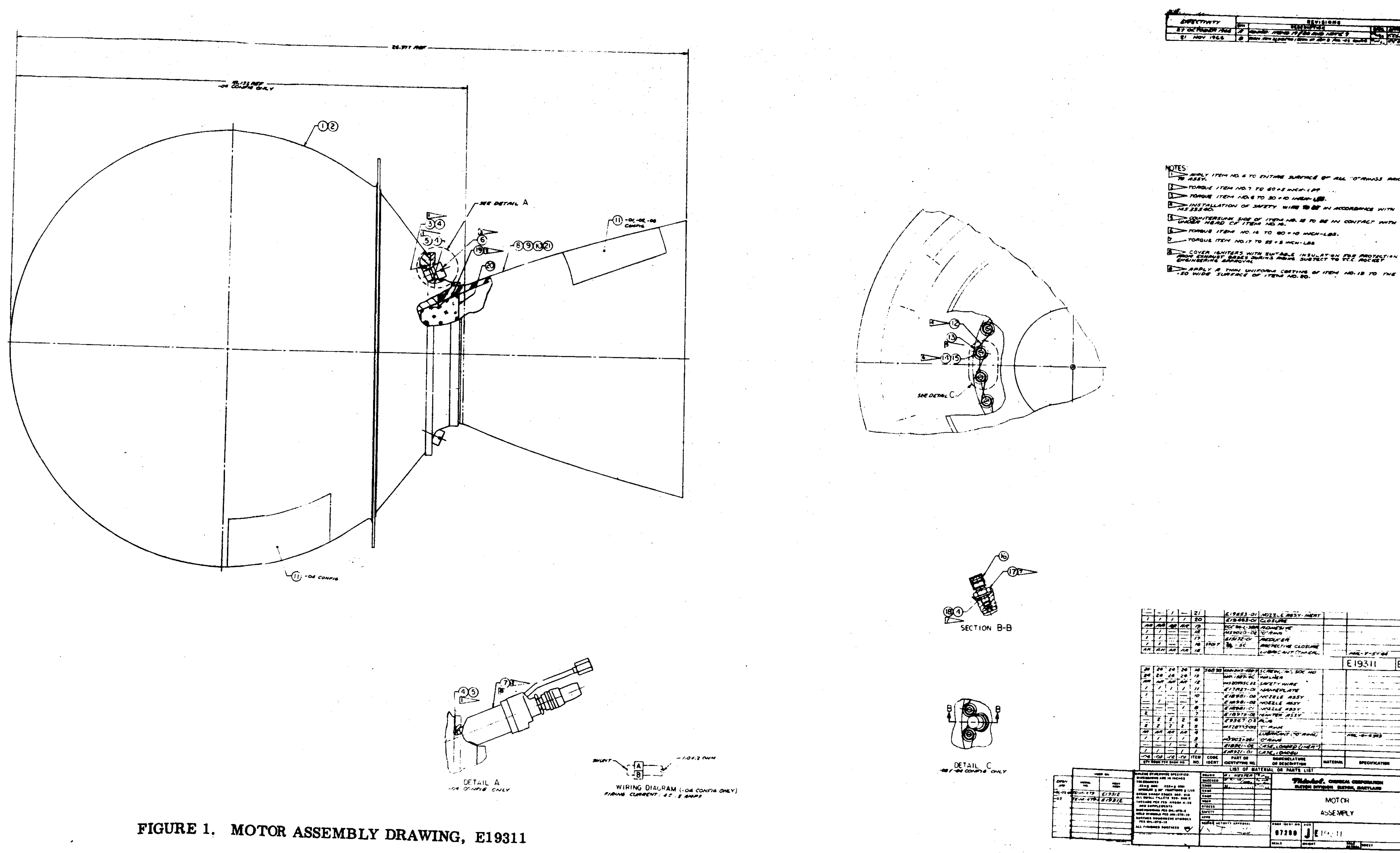

FIGURE 1. MOTOR ASSEMBLY DRAWING, E19311

FOLDOUT FRAME 1

FOLDOUT FRAME 2

The V-44 material is bonded in place using the TYPLY T/W adhesive system. The "T" material is a primer for the case; the "W" material is the case to insulation bonding agent.

The insulator is designed to include grain stress-relief boots at the head and aft ends. These "boots" permit thermal expansion and contraction of the grain without adversely affecting the propellant to liner interface. (Details of the "boots and disc and their installation are shown on TCC Drawings E18994, E18995, E18496, and E18984, respectively.)

3. Propellant and Liner

The motors are lined with TL-H-304 liner before loading. Approximately 0.29-pound of this liner is painted into the case. After the liner is cured, TP-H-3062 propellant is loaded into the case, cured, and radiographically inspected. The grain is an eight-point star configuration as depicted in TCC Drawing E18921.

4. Nozzle Assembly

The nozzle assembly, P/N E18981, consists of the insulated aft closure (E18978), exit cone (E18932), and carbon throat insert (E18942). The aft closure is manufactured from a machined 7076T6 aluminum forging per Drawing E18930. The surfaces exposed to the combustion gases are insulated with vitreous silica phenolic rings which are bonded in place.

The exit cone, P/N E18932, is also fabricated from MX2625 and is contoured to an equivalent average expansion ratio of 53:1. It is screwed into and bonded to the aft closure.

The nozzle assembly is attached to the case by KS81ZH3-438-9 cap screws. These are torqued to 60-inch-pounds during the assembly operation.

5. Pyrogen

The motor is ignited by a redundant ignition system, E18979. Each pyrogen contains a 1A/1W no-fire initiator, E16560. The pyrogen exhausts into the motor through openings in the aft closure. The pyrogen case, E18637, and head cap, E14290, are machined from 303 SST. The pyrogen propellant grain, E15456, is an AP[4]-polysulfide composite formulation designated TP-E-8035. The 1A/1W initiators discharge into a container, P/N E14667, that consists of two perforated nickel alloy diaphragms, a nickel alloy ring and approximately 1.25 grams of $BKNO_3$[5] pellets (2A)

[4] AP = Ammonium perchlorate.
[5] $BKNO_3$ = Boron potassium nitrate.

The initiators contain a single bridgewire having 1.1±0.1-ohm resistance. The recommended firing current is 4.0 amperes.

C. DESIGN ANALYSIS

The following theoretical analyses were conducted during the course of this program and have been submitted to NASA:

Stress Analysis, RER-435
Weight, Balance, and Mass Moment of Inertia, RER-439
RAE Plume Boundary Profile Study
RAE Exhaust Plume Radiation Study
RAE Case Temperature Profile

A brief summary of the analyses and results is included below.

1. Stress Analysis

This analysis was prepared during the case design phase in order to ensure the structural adequacy of the TE-M-479 motor case, closure, and closure attachment bolts. A 1.50 ultimate load factor was used for the analysis. Minimum thicknesses and minimum mechanical strength of the material were used in order to develop the worst membrane stress situation.

Design and analysis of the motor case was based on a minimum case wall thickness of 0.038 inch with a minimum yield strength of 155,000 psi and minimum ultimate strength of 165,000 psi for 6Al-4V titanium at room temperature.

The analysis is slightly conservative because the non-linear behavior of stress with pressure caused by geometry change was not taken into account. For spherical pressure vessels, the reduction in bending stress across the membrane at transition joints is slight when considering non-linearity of stress and pressure.

The stress analysis determined that the motor case would withstand 990 psi chamber pressure (bulk yield) and withstand 1485 psi chamber pressure (burst). The analysis checked stress at the constant thickness membrane of the forward hemisphere, the membrane transition zones for shelf attachment and the case-closure boss rings. Based on these results, the stress condition at the weld zone of the case girth was considered sufficiently low (based on a 25% membrane build-up); no formal analysis was performed for this particular case zone.

The analysis indicates that the critical stress condition (1485 psi at the minimum case strength and minimum thickness condition) is at the junction of constant-thickness case wall to the forward transition section for ultimate pressure (P_{ult}). Although the case is analytically marginal at this location there were no problems because minimal conditions were used for the analysis. The probability of this occurring in actual manufacturing operations is very low.

The closure and closure attachment bolts (300 type SST, 125,000 psi tensile ultimate) were also investigated at a condition of P_{ult} = 1485 psi. Margins of safety are adequate for these two structural components. Interaction forces between the motor case and closure were determined by a simultaneous solution of discontinuity forces beginning at the forward case section and continuing throughout the aft case section and closure elements.

Shear interaction between case and closure is carried by the closure shear lip. The closure bolts are under a combined loading of axial tension (caused by ejection and rotational flange separation forces) and bending (caused by the bending of the closure flange).

All components were investigated for two pressurized conditions. They were: 1) motor static firing, and 2) hydrostatic-burst test which was set-up to determine the effects of a solid plug across the closure port opening. The stress analysis resulted in a motor design which would withstand the specified operating conditions.

2. Weight, Balance, and Mass Moment of Inertia

The weight, center of gravity, and mass moment of inertia of the motor components were calculated from detail drawings by dividing the components into simple geometrically-shaped elements and programming the dimensions of these elements on a computer. The computer calculated the mass properties of the components and also combined the components to obtain the mass properties of the loaded and empty motor configurations.

The dimensions used in these calculations were the nominal dimensions (disregarding the tolerances) except for the case wall thickness. The mean dimension was used for the case wall thickness because of the +0.006-inch tolerance which is 16 percent of the basic thickness of 0.038 inch and is equivalent to 0.95 lbs.

The original calculated weight of the propellant is 154.2 lbs; the actual propellant weight, which is controlled by casting to a weight rather than to a dimension, is $153.5 \pm \frac{1.0}{0.0}$ pounds.

The following data present the results of the original calculations:

Weight and Center of Gravity

Motor Condition	Weight lbm	Longitudinal C. G. (X_{cg}) in.	Lateral C. G. (Y_{cg}) in.	Vertical C. G. (Z_{cg}) in.
Loaded	174.6	- 5.75	0	0
Empty	20.4	- 1.23	0	0

Mass Moment of Inertia

Motor Condition	I_{xo} lbm in.^{2}	I_{yo} lbm in.^{2}	I_{zo} lbm in.^{2}
Loaded	5575	6092	6079
Empty	670	1149	1136

Figure 2 is the reference data diagram for the motor. A weight summary including the actual propellant weight for the unit is presented below:

Item	Weight, (lbm)
Case	8.80
Head End Insulation	1.28
Head End Plug and Adhesive	0.04
Aft Case Insulation	1.80
Adhesive Insulation to Case	0.29
Liner	0.29
Aft Closure	1.47
Insulated Aft Closure	0.14
Insulated Aft Closure	0.12
Exit Cone	3.49
Insert	1.53
Propellant	153.50
Igniter	0.41
Igniter	0.41
Hardware	0.27
Loaded Motor	173.85
Empty Motor	20.35

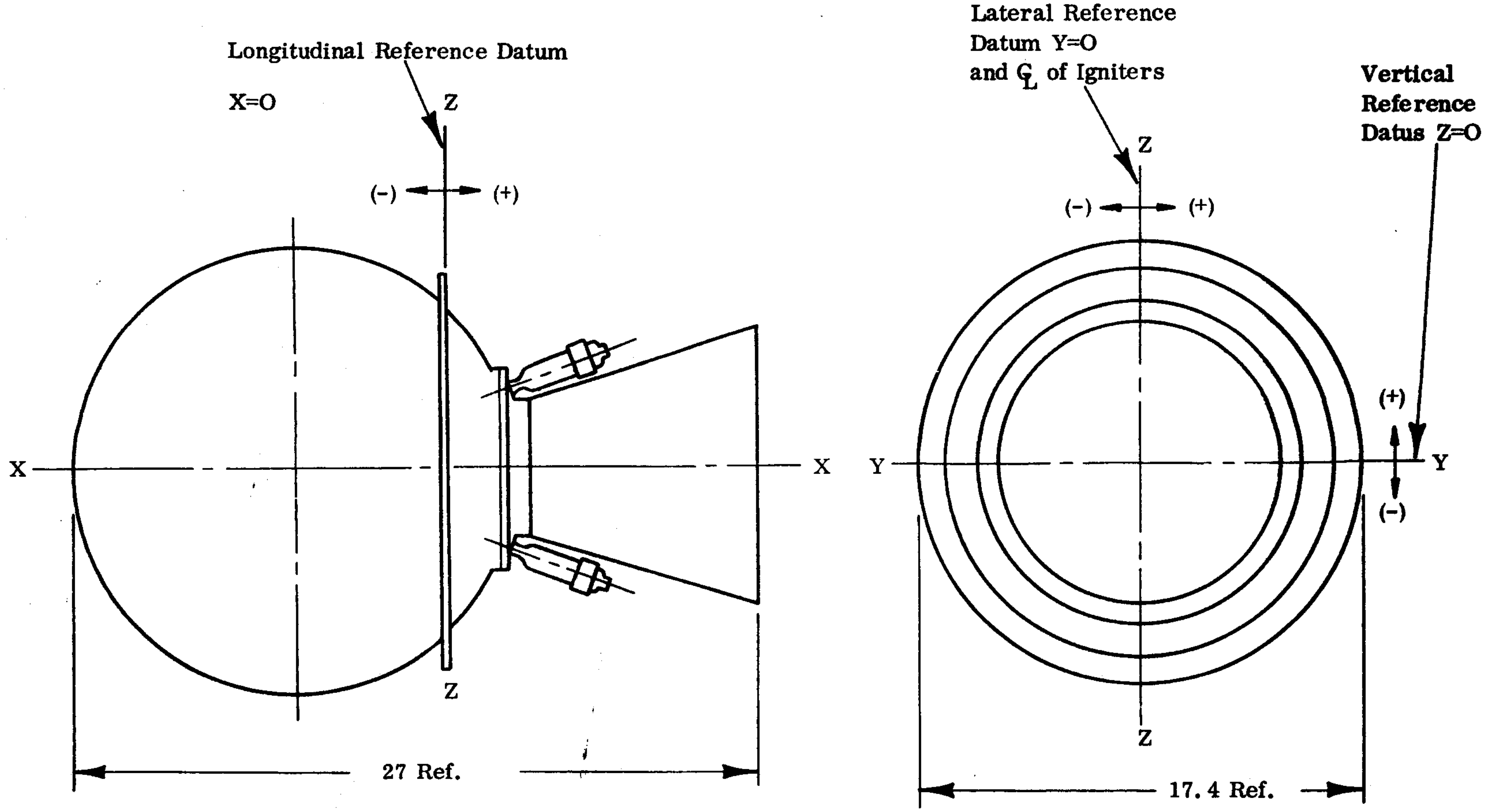

FIGURE 2. REFERENCE DATA DIAGRAM, TE-M-479 ROCKET MOTOR

3. RAE Plume Boundary Profile Study

An exhaust plume analysis was conducted to determine if the plume will impinge on the spacecraft. The results of the exhaust plume study indicate that there will be particle impingement on a portion of the paddles of the spacecraft; however, we did not estimate the size and density of the particles as they strike the paddles.

The maximum turning angle of the exhaust gases was determined by using the Prandt-Meyer function for maximum nozzle exit conditions. Based on a 14.2-degree nozzle half angle, the maximum turning angle is 125.2 degrees. Since any turning angle greater than 90 degrees will result in impingement on the spacecraft solar panels, a portion of the plume is expected to flow towards the spacecraft.

The Mach number and the temperature profile within the exhaust plume were also determined using the Prandt-Meyer function and the isentropic temperature relationship. Using a stagnation temperature of 6122°R and a gamma of 1.20 the following relationship between the temperature profile of the gas flow and the turning angle was established:

Exhaust Plume Mach Number	Exhaust Plume Temperature (°R)	Exhaust Gas Turning Angle (degrees)
10	556	69.9
14	297	85.1
20	147	96.9

It was shown that the average temperature of the gas in the region of the paddles was less than 200°R for a 1.20 gamma. Even under the worst case condition of 1.0 gamma this temperature would be less than 300°R.

for their consideration

The results of this analysis were presented to NASA in the final spacecraft design for their consideration.

4. Exhaust Plume Radiation Analysis

The Stefan-Boltzman Law was used to calculate the heating rates resulting from the rocket exhaust at various locations on the spacecraft. The apparent emissivity of the motor exhaust was obtained analytically by considering the radiation from an infinite conical gas body of uniform temperature and composition.

An effective gas temperature of 1880°R was used to account for the varying composition throughout the exhaust plume. The analysis shows that the greatest heating rate occurs on the honeycomb skin nearest the intersection of the side wall which is parallel to the center line (℄) of the motor and the aft surface. This rate is 0.61 BTU/ft^2-sec. The greatest heat input to the solar paddles occurs at the point nearest the motor exit plane. This rate is 0.52 BTU/ft^2-sec.

The above information is only for radiative heating; it does not take into account convective heating or heat transfer caused by the energy of particle impingement.

5. Case Temperature Profile

An analysis of the case temperature heat transfer was conducted during the course of the program. The following locations were considered (based on minimum insulation and case thickness areas):

Location	Angular Orientation, degrees
Forward Hemisphere	31° from ℄
Forward Hemisphere	65° from ℄
Girth (equator)	90° from ℄
Aft Hemisphere	37° from ℄

The analysis was conducted in two phases: Phase I considered the heat transfer from 0 to 5 minutes after motor ignition, and Phase II considered the heat transfer from 5 to 20 minutes after ignition. Minimum insulation thickness was used in the analysis to evaluate the worst case conditions.

The Phase I prediction was based on using an effective film coefficient determined from rocket motors having a similar internal geometry. For the Phase II prediction, an analytical procedure was used based on radiated heat transfer. This analysis included the thermal energy of the case, emissivity, Stefan-Boltzmann constant, and the case temperature. Temperatures at various time stations are presented below:

Time, min	Forward Hemisphere, 31° ℄, °F	Forward Hemisphere, 65° ℄, °F	Girth, °F	Aft Hemisphere, 37° ℄, °F
0.25	80	80	80	125
0.50	235	140	140	230
0.75	325	225	225	295
1.00	385	290	290	345
1.5	450	365	365	395
2.0	495	425	425	430
5.0	550	440	440	445
10	390	335	335	335
20	240	220	220	220

D. MANUFACTURING AND TESTING

The interior surfaces of each motor case are painted with 0.29 pound of TL-H-304 liner. This material serves to bond the propellant to the insulation and relief "boots". The lining operation was performed on all of the motors on January 11, 1967.

The internal star grain configuration for this motor is produced by casting the propellant around a fixed-in-place core (or mandrel). The motors required (6 test, 4 delivery) were loaded from one 150-gallon batch of propellant (PV16-659) on January 13, 1967. The motors were then placed in the curing oven for 136 hours at 135°F.

After curing of the propellant and cooldown of the assemblies, the cores were removed, the propellant flashing was trimmed and the loaded motors were X-rayed and found to be acceptable. On several motors, a small disc of propellant was located between the end of the core and the phenolic disc. Due to the small volume of propellant and the fact that the allowable surface area increase of the acceptance criteria was not exceeded on any units, this propellant disc was not removed.

At the same time the motors were loaded, nozzle assembly operations were begun. The contoured exit cones were fit into the aluminum aft closure and bonded in place. The Graph-i-tite semi-finished nozzle inserts were bonded into the aft closure with Epon 913. The insert throat were final contoured after placement in the closures. The nozzle assembly was time sequenced in steps; the nozzles were assembled and the throats sized based on the results of propellant sample ballistic tests and static motor firings.

1. Development Program

a. Hydroburst Test

The first motor case received from the case subcontractor was designated for the hydroburst test (Reference 1).[6] The case was instrumented with three rosette strain gages in the case forward membrane section. It was then installed into the test arrangement which was heated to 120 ± 5°F. The pressure was increased to 800 psi as rapidly as possible and held for 24 seconds. The case pressure was then increased at a rate of approximately 300 psig per minute. (If 1540 + 10 psig was reached before failure occurred, the pressure was to be released and the test terminated to save the case). The maximum expected operating pressure for this motor is 990 psig; the minimum burst is 1.5 times 990 psig, or 1485 psig. The "stop point" was set at a 1.55 factor of 1540 psig. At 1511 psig, a circumferential shear failure of the aft closure shear lip occurred. No loss of pressure was experienced; however, the pressure was released at this point and the case saved for mock-up purposes. The assembly had passed the 1.5 safety factor and the test was considered successful. Subsequent inspection of the case revealed the shear-lip failure and it is probable that the case would have withstood a higher pressure before bursting. Appendix C contains a photograph showing the assembly and the failed aft closures. Figures 3, 4 and 5 show plots of strain versus chamber pressure.

b. Development Test No. 1

The motor chosen for the first static test was PV16-659-9. Before assembly, the exit cone was truncated for a sea level test to an expansion ratio of 11.3/1. After assembly, the motor was leak checked and released for testing, where it was instrumented and conditioned to 70 ± 10°F. The motor was installed in the spin test stand which was restrained from spinning. The primary purpose of the first test was to evaluate initially the motor components and obtain pressure and temperature data. On January 27, 1967, the motor was static tested. Pressure, time, and temperature measurements indicated that the test was successful. Post-test examination of components confirmed the satisfactory test. The Graph-i-tite G-90 insert experienced 25 percent area erosion which was greater than that predicted. However, reduced data indicated that the performance was satisfactory. Figure 6 shows the pressure-time and vacuum thrust-time history for this motor. A case temperature evaluation was performed and is contained in Test Report E25-67 (Reference 2). Actual measured temperatures were close to those predicted for this motor during the motor burn time. However, because of insulation burning in the presence of air after motor operation and the subsequent water quenching, post-fire thermal data are not the same as those from a motor actually experiencing a space environment. Quenching was used to terminate "cooking" of the insulation as quickly as possible, so that the insulation could be inspected for post-test condition. This procedure was used on three of the tests conducted at sea level.

[6] References are detailed in Section III.

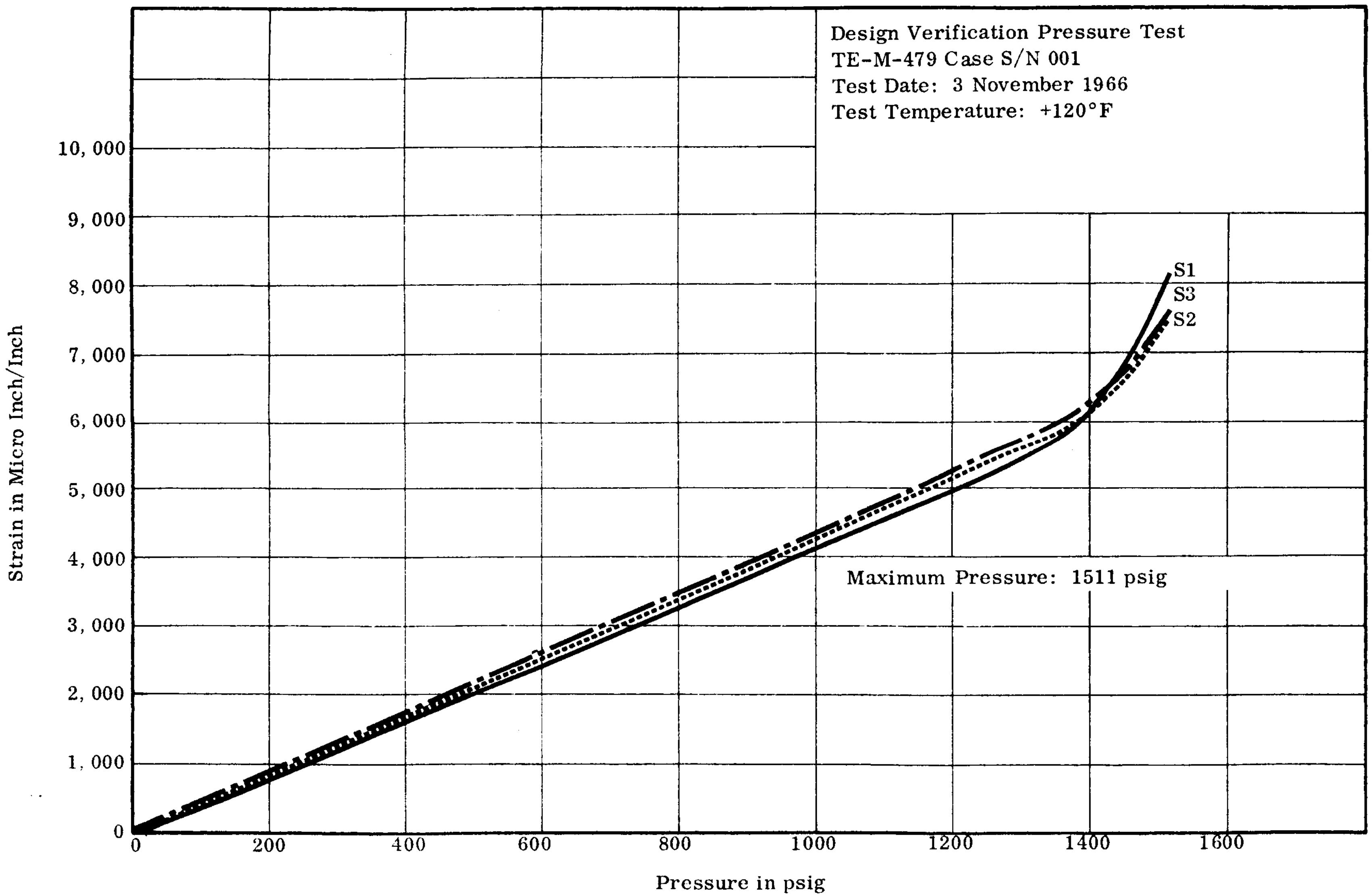

FIGURE 3. STRAIN VERSUS PRESSURE, TE-M-479, S1, S2, S3

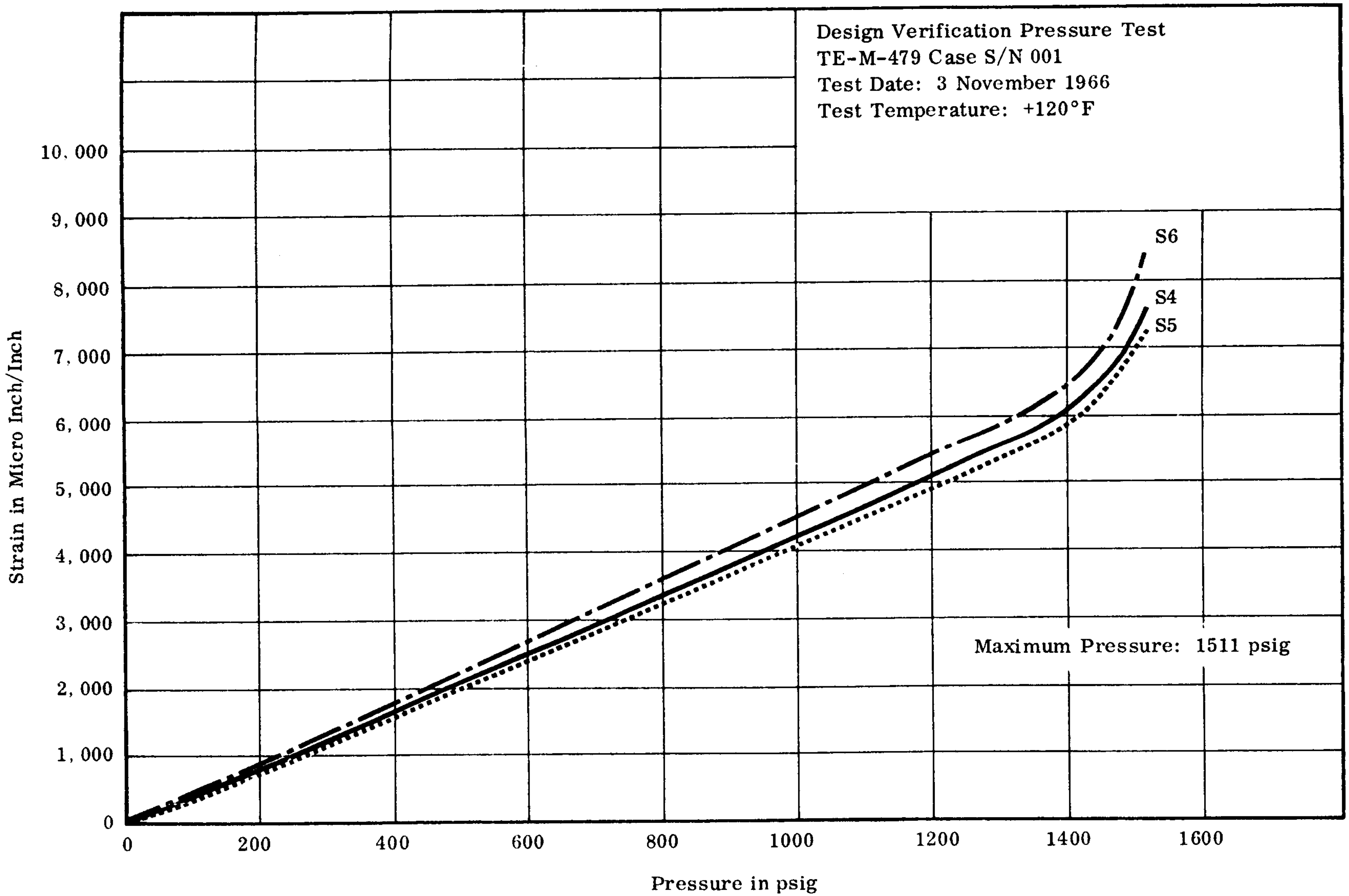

FIGURE 4. STRAIN VERSUS PRESSURE, TE-M-479, S4, S5, S6

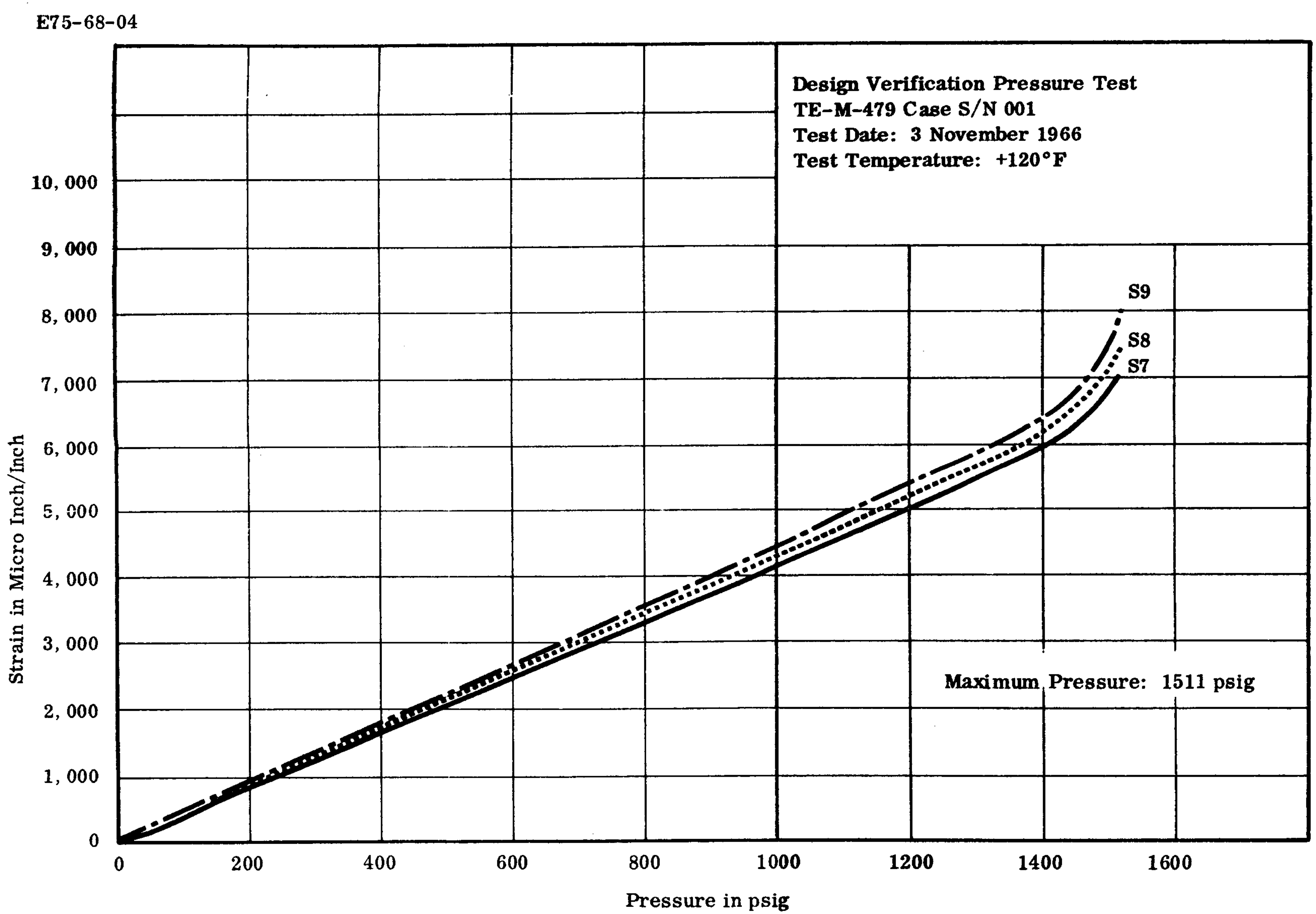

FIGURE 5. STRAIN VERSUS PRESSURE, TE-M-479, S7, S8, S9

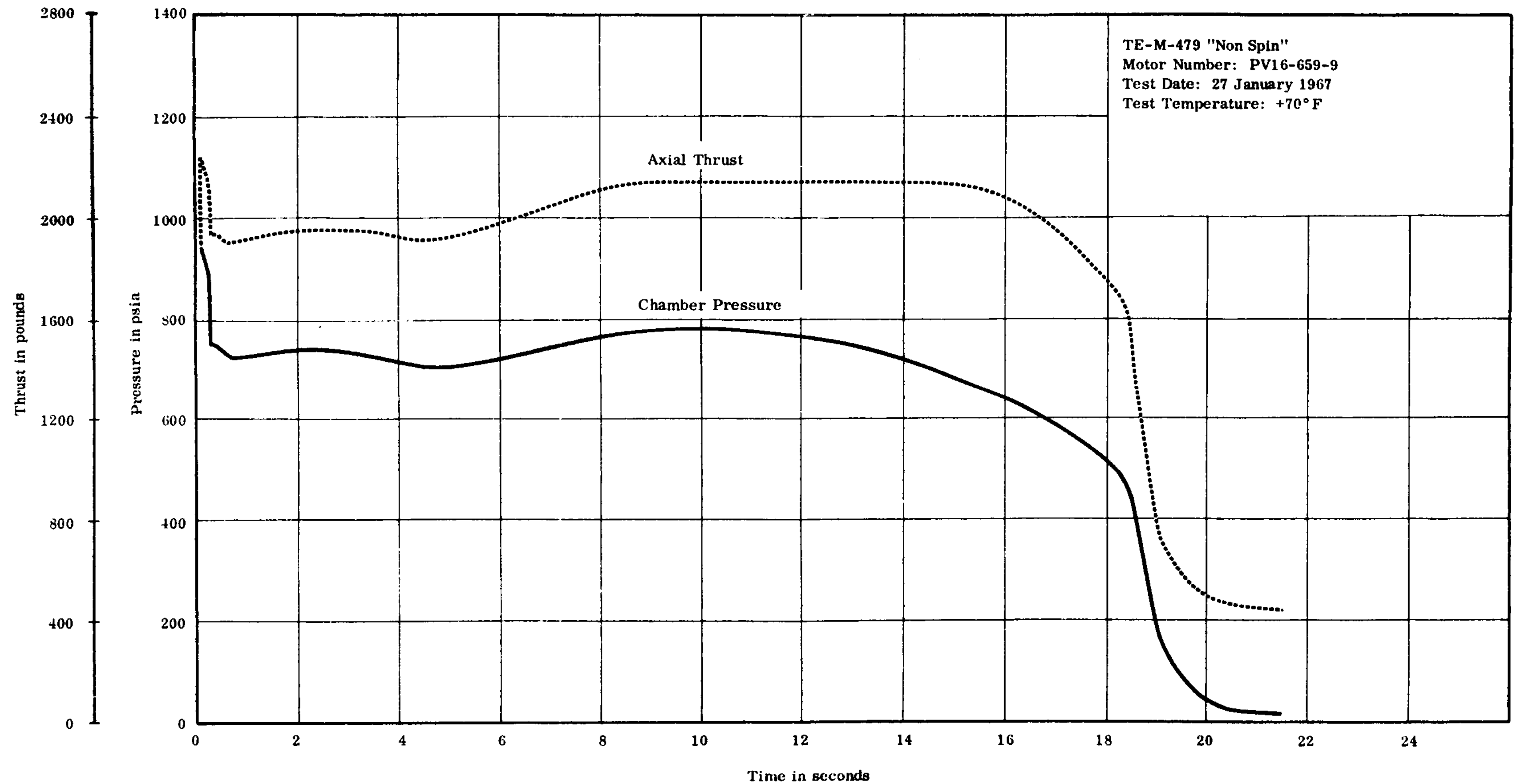

FIGURE 6. PRESSURE AND VACUUM THRUST VERSUS TIME. PV16-659-9

Following the first test, a new batch of Graph-i-tite G-90 was procured to investigate the higher than predicted erosion which occurred on the first test. This graphite was used in the third test and is covered in the discussion of that test (I. D. 1. d).

c. Development Test No. 2

Motor PV16-659-1 was vibrated through the random and sinusoidal levels specified in NASA Specification 67-58, at Component Evaluation Labs, El Monte, California. The motor was X-rayed before and after the vibration and no defects were found. A complete description of the test can be found in Test Report E36-67 (Reference 3). Following vibration and X-ray, the nozzle was truncated and the motor reassembled and conditioned to 70°F. On February 16, 1967, the motor was fired while spinning at 150 rpm. Motor performance was satisfactory and the throat erosion decreased to 17. 4 percent. The throat did not exhibit the valley-peak erosion characteristic apparent in the first test. This difference was due to the spin environment of this test. Calculated vacuum total impulse was 45, 300 lb-sec. (The sea level data were corrected to vacuum conditions.) The test stand was calibrated. The thrust data for this spin test and the following two were normalized to account for test stand calibration (see Figure 7).

While the second motor was being processed and tested, the nozzle for the third test motor was being assembled. The nozzle throat insert was replaced with one made from the second billet of Graph-i-tite G-90 material. The throat diameter was adjusted from 1. 417 to 1. 400 inches to increase the average operating pressure level to the desired level. The inlet section radius on this insert was also thickened slightly on the outside diameter in an attempt to reduce nozzle throat erosion.

d. Development Test No. 3

The third motor fired was PV16-659-2. This motor was temperature cycled from ambient to 0°F and held for 22 hours, then to 120°F for 22 hours, after which it was X-rayed and reconditioned to 120°F. It was then installed in the test stand and on February 17, 1967, static tested at 120°F, while spinning at 150 rpm. Again, all test objectives were met. A complete description of this test is found in Reference 4. Thrust versus time history for this test is shown in Figure 8. The total impulse corrected to vacuum conditions was 44, 850 lb-sec. The throat erosion with the new graphite was 16. 7 percent, which was not significantly different from Test No. 2. At this time, it was decided to use the original graphite for the remaining test and delivery motors. Although the erosion was higher than originally expected, the total impulse requirement was met and the insert was demonstrated to be structurally sound.

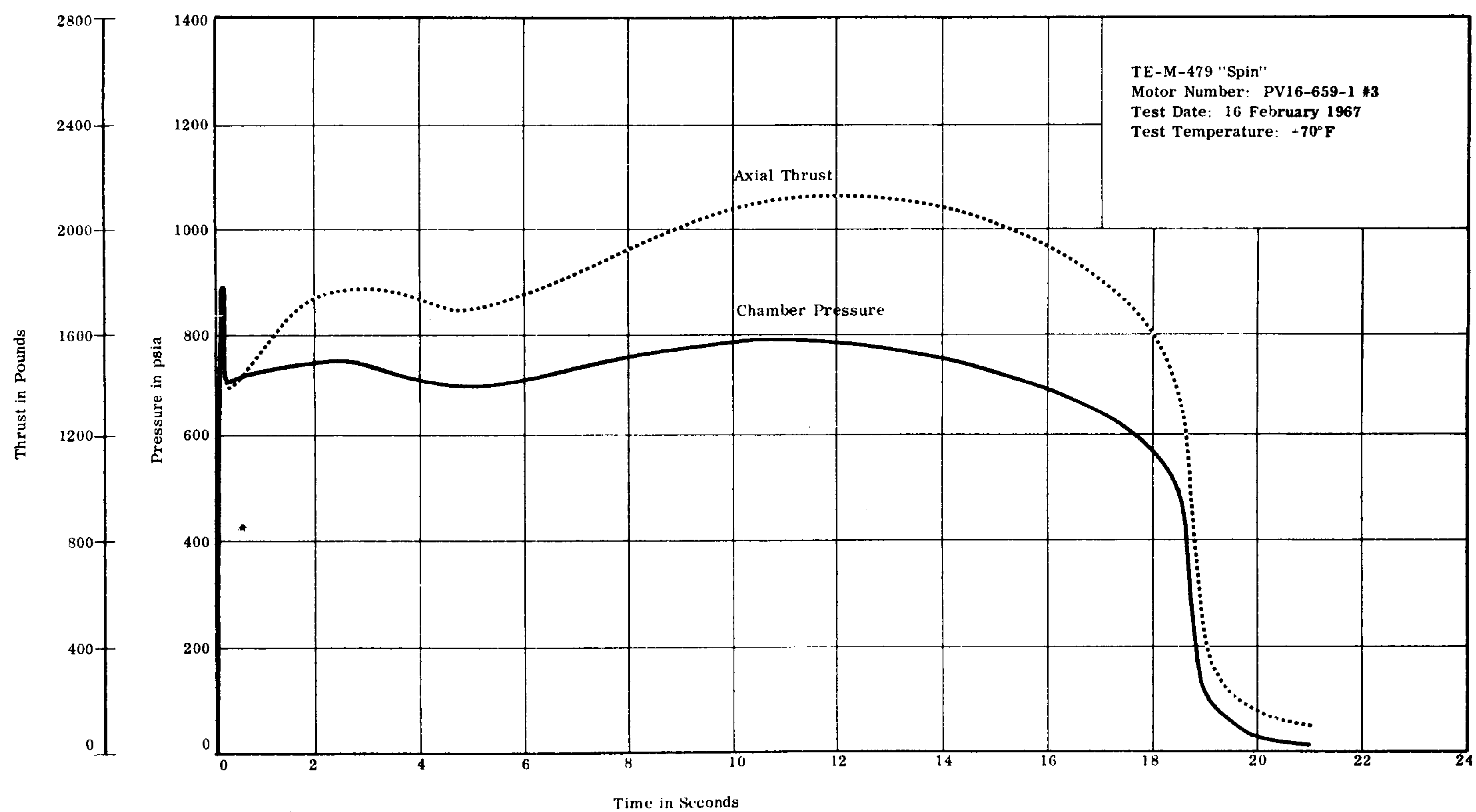

FIGURE 7. PRESSURE AND THRUST VERSUS TIME. PV16-659-1

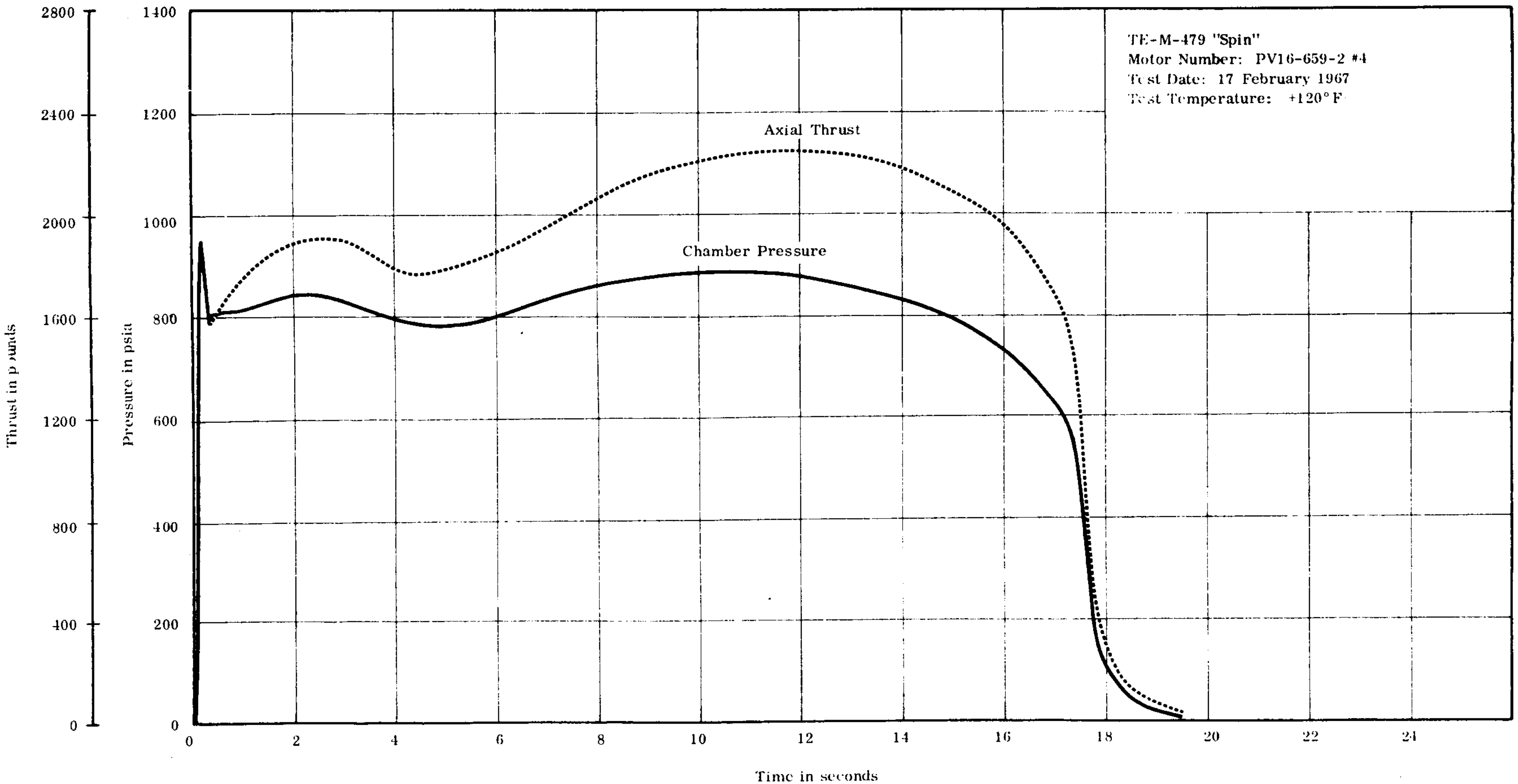

FIGURE 8. PRESSURE AND THRUST VERSUS TIME PV16-659-2

e. Development Test No. 4

Motor PV16-659-3 was designated for the fourth test. The original nozzle insert configuration was used in this motor and the throat diameter was 1.400 inches. This motor was temperature cycled, ambient to 120°F, held for 22 hours, then to 0°F for 22 hours. It was X-rayed and reconditioned to 0°F and fired while spinning at 75 rpm on February 24, 1967. A complete description of this test can be found in Reference 5; Figure 9 shows the pressure versus time history. This test was completely successful. The total impulse, corrected to vacuum conditions, was 44,190 lb-sec and the throat erosion was 17.1 percent.

This completed the four-motor development program and was the last of the tests conducted at Thiokol-Elkton.

2. Qualification Program

Two TE-M-479 motors, PV16-659-7 and PV16-659-10, were shipped to AEDC in early March, 1967. The throat diameter for these motors was adjusted to 1.373 inches to provide the required operating pressure for flight motors. The motors were inspected and assembled to the mating hardware. The four igniters were also inspected and resistance checked. The motors were instrumented and mounted in the spacecraft. The motor and spacecraft were aligned in the test stand and the motor "misalignment" measured at the same time. The "misalignment", the angle between the centroid of the nozzle and a line perpendicular to the mounting flange, was 2.58 minutes and 3.54 minutes for motor PV16-659-7 and -10, respectively. Each motor was leak checked after the pyrogens were installed. Motor S/N 7 was the first tested. This motor was conditioned in the test cell to 40°F. The cell was evacuated to 124,000 feet simulated altitude and the motor fired while spinning at 75 rpm on March 24, 1967. The motor was spun for 45 minutes after the firing and temperature data were recorded during this period. The nozzle insert was injected into the motor upon blowback, causing the measured post-test temperature data to be different from that expected in an actual flight. AEDC reduced data indicate a vacuum total impulse of 44,406 lb-sec (corrected to hard vacuum). Thiokol reduction of these same data resulted in excellent corroboration of this parameter; Thiokol obtained 44,379 lb-sec (corrected to hard vacuum). Both figures are well within the 44,500 ± 440 lb-sec specification limit. The average pressure was 774 psia and the specific impulse was 289.97 lb-sec using the AEDC total impulse figure. Throat erosion for this test was 22.7 percent. A complete discussion of this test is covered in Reference 7.

The test of the second motor (S/N 10), tested on March 31, 1967, was similar that of S/N 7, except that it was conditioned to 90°F prior to the test. Motor performance was again near perfect, the AEDC and Thiokol total impulse calculations being 44,583 and 44,563 lb-sec, respectively (corrected to hard vacuum). The average

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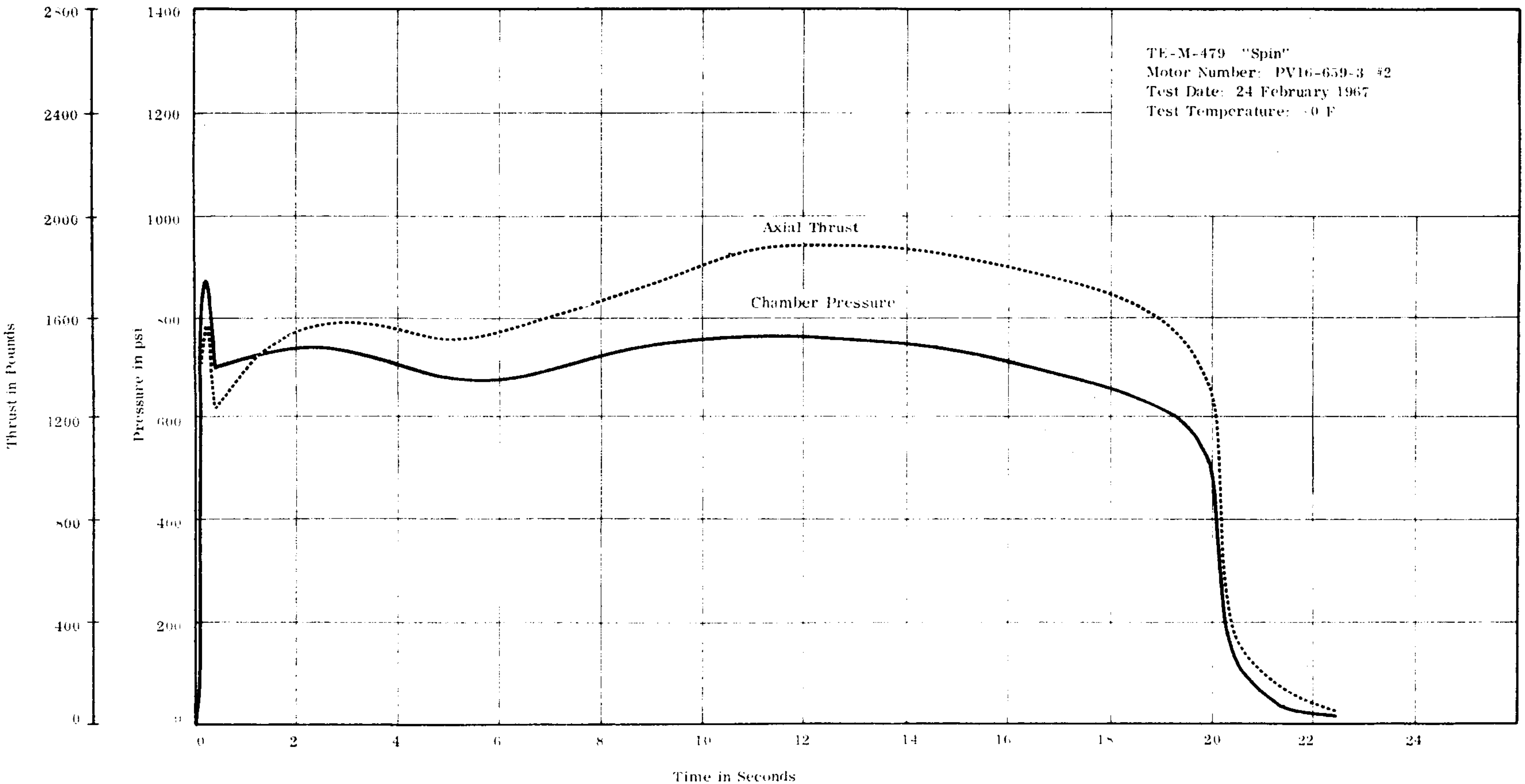


FIGURE 9 PRESSURE AND THRUST VERSUS TIME, PV16-659-3

motor chamber pressure was 830 psia and the specific impulse was 290.63 lb-sec, using the AEDC total impulse figure. Throat erosion was 24 percent. Plots of thrust versus time for the AEDC tests are included in Appendix B. Reference 7 also covers the details of this test.

A 0-1 psi gage was used to record low level pressure measurements after burnout of the motor. Each of the two tests experienced low level pressure of a maximum magnitude of 0.15 psia for approximately 40 seconds after motor burnout. These readings resulted from post-test smoldering of the rubber insulation.

Side forces of the spacecraft/kick motor were measured during the firing. The magnitude of these forces ranged between one and two pounds of force.

RER-432 was revised to reflect the performance obtained on the AEDC tests and is presented as Appendix II.

Before each AEDC test, the thrust misalignment of each motor was measured. Appendix A shows the comparative misalignments and motor data for each of the AEDC tested motors. Appendix III shows pre- and post-test photographs of each development motor.

3. Performance Analysis

A summary of the data resulting from the test effort is presented as Appendix A. The details of each test were previously furnished to NASA (References 2 through 7). Based on the two AEDC tests, the motor demonstrated an average total impulse of 44,471 lb-sec at vacuum conditions. The final performance is based on the AEDC tests only due to the inaccuracies of thrust measurement of sea level test data. A comparison of the required and actual total impulse is presented below:

	Required	Actual
Total Impulse, lbf-sec	44,500	44,471[7]
Deviation from nominal Total Impulse, lbf-sec	± 440	+62 ~~-92~~ -111

Thiokol concludes that this motor meets all NASA requirements for the RAE program.

[7]Based on AEDC data only.

E. DELIVERY

Based on the successful completion of the AEDC tests, the four delivery motors and eight delivery pyrogens were completed and log books submitted to NASA. Prior to this submittal, NASA measured the motor misalignment which in each case was well within the 15 minute specification limit (See Appendix A). The delivery motor and pyrogen serial numbers are as follows:

Motor Numbers	Pyrogen Numbers (2 per motor)
PV16-659-4	07299-001-1-5, 07299-001-1-6
PV16-659-5	07299-001-1-7, 07299-001-1-8
PV16-659-6	07299-001-1-9, 07299-001-1-10
PV16-659-8	07299-001-1-11, 07299-001-1-12

Final acceptance and buy-off was made at Thiokol-Elkton. The motors are now in storage awaiting shipment to the Western Test Range for flight.

II. CHRONOLOGY, RAE KICK MOTOR DEVELOPMENT, QUALIFICATION, AND DELIVERY PROGRAM

Program Start	May 5, 1966
Hydroburst 1 Case	November 2, 1966
Initial Receipt of Motor Cases	November 30, 1966
Receive Insulated Cases	January 9, 1967
Load 10 Motors	January 13, 1967
Begin Motor Assembly	January 25, 1967
Static Test Motor PV16-659-9	January 25, 1967
Temperature Cycle and Spin Test Motor PV16-659-2	February 17, 1967
Temperature Cycle and Spin Test Motor PV16-659-3	February 24, 1967
Vibrate Motor PV16-659-1	February 8. 1967
Spin Test Motor PV16-659-1	February 16, 1967
AEDC Altitude Test Motor PV16-659-7	March 24, 1967
AEDC Altitude Test Motor PV16-659-10	March 31, 1967
Complete final buy-off of 4 delivery motors	December 15, 1967

III. REFERENCES

Reference No.	Description
1	Hydroburst Test Report
2	Thiokol Test Report E25-67
3	Thiokol Test Report E36-67
4	Thiokol Test Report E31-67
5	Thiokol Test Report E42-67
6	Thiokol Test Report E79-67
7	AEDC Test Report TR-67-127 (covers two tests)

IV. NEW TECHNOLOGY

Not applicable for this contract.

APPENDIX I

MOTOR DATA SUMMARY

MOTOR DATA SUMMARY

Motor Number	Propellant Weight lbs	Motor Weight lbs	Environmental Tests	Test Date	Firing Temperature °F	Spin Rate, rpm	Ignition Delay, sec.	Maximum Pressure, psi Ignition	Maximum Pressure, psi Operation	Maximum Thrust, lbf Ignition	Maximum Thrust, lbf Operation	Action Time, sec	P_{avg} T_b psi	Throat Erosion, %	I_{sp} sec	I_{tot} lbf-sec	Pyrogens Activated	Thrust Alignment, (arc minutes)
PV16-659-9	153.27	170.82 (sea level nozzle)	Cond. 70° F	Jan. 31, 1967	70	0	0.043	830	783	1971	1879	19.410	717	25.0	226.1	34,657	2	--
PV16-659-1	153.16	170.75 (sea level nozzle)	70° F Vibration	Feb. 16, 1967	70	150	0.030	891	788	1730	2120	19.180	729	17.4	230.4	35,292	2	--
PV16-659-2	153.27	171.12 (sea level nozzle)	Temperature Cycle 60°-0° F (22 hrs) 0°-120° F (22 hrs)	Feb. 17, 1967	120	150	0.025	950	890	1848	2240	17.990	818	16.7	230.4	35,316	2	--
PV16-659-3	153.38	171.10 (sea level nozzle)	Temperature Cycle 60°-120° F (22 hrs) 120°-0° F (22 hrs)	Feb. 24, 1967	0	75	0.114	873	762	1586	1880	20.586	715	17.1	223.3	34,250	2	--
PV16-659-7	153.14	174.14	Cond. 40° F	Mar. 24, 1967	40	70	0.070	972	847	2486	2638	19.190	774	22.7	289.8	44,379	1	2.58
PV16-659-10	153.40	174.05	Cond. 90° F	Mar. 31, 1967	90	70	0.060	1063	909	2750	2865	18.090	830	24.0	290.5	44,562	1	3.54
PV16-659 (Deliveries)																		
-4	153.21	174.12	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-	2.88
-5	153.47	174.22	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-	1.12
-6	153.26	174.32	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-	2.17
-8	153.40	174.12	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-	0.99

FOLDOUT FRAME 1

FOLDOUT FRAME 2

APPENDIX II

RER-432, REVISION A

Thiokol
CHEMICAL CORPORATION
ELKTON DIVISION
ELKTON, MARYLAND

ROCKET ENGINEERING DEPARTMENT REPORT

RER-432
REVISION A

INTERNAL BALLISTICS REPORT
TE-M-479
ROCKET MOTOR

27 NOVEMBER 1967

Prepared By Joseph H Scarborough

Approved By K. Chenard
Project Engineering Section

Reviewed By D R Reed

Approved By L M Dyson
Rocket Engineering Department

Reviewed By W. G. Andrews
SPECIAL PROJECTS GROUP

RE2-14 (1)

FOREWORD

The Internal Ballistic Report (RER-432) has been revised to reflect the performance obtained on simulated altitude tests.

1.0 SUMMARY

Presented in paragraph 4.6 and Figures 1 and 2 is the performance for the temperature specified in the NASA specification (Ref. 5.1.1). In order to evaluate the simulated altitude test data, the following parameters were obtained:

1. Ballistic parameters (C^*, C_d, r, π_k & percent sliver)
2. Nozzle throat area vs percent web
3. Propellant surface area vs percent web

The following observations were made:

1. A staggered ignition of the PYROGEN igniters by ignition of only one, yields motor ignition pressures that are essentially the same as when both PYROGENS are ignited simultaneously.
2. A spin rate of 75 RPM had no apparent ballistic effect; however, the magnitude of the throat erosion and its profile was changed significantly from that obtained on a unit tested without spinning.
3. The propellant burn rate of the TE-M-479 was 7.7% higher than the rate obtained from 5" propellant batch control motors.

2.0 CONTENTS

2.2 List of Illustrations

3.0 DISCUSSION

This report is based on data from two motor firings conducted at Arnold Engineering Development Center (Test Report AEDC-TR-67-127 [Ref. 5.1.2]). The tests were conducted with the motors rotating about their thrust axis at 75 RPM and operating at a nominal simulated altitude of 120,000 feet.

3.1 Evaluation Method

A preliminary evaluation of the test data was made using the Thiokol-Elkton Computer Program E-40286, Evaluation of Throat Area and Surface Area Time Histories (Ref. 5.1.3). Ballistic parameters and throat area, surface area vs time histories were obtained. (The results are shown in Figures 3 & 4 and in Appendix 7.0.)

Further evaluation of the data was made using Computer Program E-40305, Internal Ballistic Analysis for Gas Generators (Ref. 5.1.4). This program was utilized to permit a study of the effects of PYROGEN ignition upon peak ignition chamber pressure and non-equilibrium effects of motor operation during ignition and tail-off transients. In order to use this program it is necessary to characterize the open air performance of the PYROGENS used in the TE-M-479. Data from E19-66, Test Report for six TE-P-386-6 Open Air Tests (Ref. 5.1.5) was used. Typical PYROGEN performance is given in Appendix 7.3. Motor PV16-659-10 (conditioned at 90°F) test data were back fitted to verify the ballistic parameters. The performance of PV16-659-7 (conditioned at 40°F) was calculated by changing the operating temperature. Pressure and thrust, actual and calculated, are ploted for comparison in Figures 5 & 6.

Predicted performance is tabulated (Ref. Section 4.6) for the temperatures specified in the NASA specification. Predicted performance for the maximum and minimum temperatures at which the units have been tested is also included. It should be noted that test data, other than the two AEDC firings, cannot be directly compared with this report because of differences in nozzle throat area.

3.2 Propellant Ballistics

The 5-inch propellant batch control motors indicate that the burn rate and pressure for batch PV16-659 were essentially nominal for the propellant as defined in T.C.C. Specification P22006 (Ref. 5.1.6). For this reason, the full scale motor predictions are considered nominal. A scale up in burn rate at a fixed pressure (830 psia) and temperature (90°F) between the 5" control motors and the TE-M-479 was determined to be

$$\frac{.307}{.285} = 1.077,$$

i.e. 7.7% higher in the TE-M-479.

3.2 (Continued)

The spin rate of 75 RPM was concluded to have little effect on the propellant ballistics; however, it had a signifinant effect upon the profile and magnitude of the throat erosion compared to that obtained in a non-spinning static test.

3.3 Ignition

Dual PYROGENS were used in the motors for ignition; however, only one was command-initiated in each of the AEDC tests. A plot of actual ignition pressure and calculated ignition pressure versus time is shown in Figures 7 and 8 for the two AEDC motor firings. Included also is a calculated plot for simultaneous ignition of both igniters. It is apparent from the plots that the second PYROGEN ignites just prior to motor maximum ignition chamber pressure. At the time of motor maximum ignition chamber pressure, the differences in mass flow rate between the two PYROGENS is small (.364 lbs/sec vs .330 lbs/sec); at that point in time their percentage of the total motor mass flow rate is also small (.69 lbs/sec vs 9.52 lbs/sec). The result is a motor maximum pressure that is relatively insensitive to the nominal 0.075 second delay in ignition of the second PYROGEN.

3.3.1 Effects of Throat Build Up

Early reduction of the nozzle throat area by condensation of combustion products onto the cool graphite throat material affected motor operation. For representative calculated values, at .001 second after the main motor chamber pressure reaches 50 psia the total mass flow rate is 1.29 lbs/sec, at .005 sec, 4.22 lbs/sec, during which time build-up occurs and subsequently rapidly erodes away. From the calculations for the 90°F condition the maximum ignition pressure is 1063 psia, the equilibrium pressure (without igniter mass flow, with throat buildup), is 967 psia, and the equilibrium pressure (without igniter mass flow and with initial throat area) is 860 psia. From this it is evident that the ignition spike is attributable to two factors, the throat build up which, for this motor, contributes about half of the pressure increase over the equilibrium pressure and the igniter mass flow, which contributes the remainder.

The purpose of this analysis was to predict the maximum ignition pressure accurately and reliably. Calculated and experimental data are compared in Figures 7 and 8 that agree quite well in time and magnitude through the pressurization transient. This comparison validates the usage of this method for predicting maximum ignition pressure.

4.0 MOTOR PARAMETERS

4.1	Propellant	TP-H-3062
4.2	Liner	TL-H-304
4.3	Grain Design	
	Type: Case bonded, internal burning, eight point star. Case Loaded Drawing E18921 Rev. B	
	Outside Diameter, in.	17.21
	Length, in	16.14
	Web Thickness, in.	5.225
	Internal Free Volume, in^3	178.
	Loading Density, %, Volumetric*	94.8
	Percent Sliver, %	2.7
4.4	Propellant Weight, Nominal, calculated, lbm	153.4
4.5	Nozzle Design (Vacuum Operation)	
	Throat Area, Average, sq. in.	1.637
	Expansion Ratio, Average	54.8
	Exit Area, sq. in., Average	89.74
	Exit Half Angle, Degrees	14.2

*Based on volume available to propellant inside liner and case insulation. The volume displaced by the submerged nozzle was considered.

4.6 Motor Performance

4.6.1 Pressure and Time Parameters (Nominal calculated values)

Motor Conditioned Firing Temperature, °F	0	+20	+45	+70	+90	+120
Pressure, Chamber, Maximum Ignition, psia	915	943	980	1019	1050	1100
Pressure, Chamber, Maximum, psia	788	813	845	878	905	948
Pressure, Chamber, Average, psia	721	744	773	803	827	867
Burn Time, seconds	19.50	18.90	18.24	17.58	17.05	16.3
Action Time, seconds	20.55	19.95	19.20	18.53	17.98	17.2
Ignition Delay Time, seconds	.080	.070	.070	.070	.060	.050
Ignition Rise Time, seconds	.011	.011	.011	.011	.011	.011
Ignition Time, seconds	.091	.081	.081	.081	.071	.061

4.6.2 Thrust and Impulse Parameters (Nominal, calculated values in vacuum)

Motor Conditioned Firing Temperature Temperature, °F	0	+20	+45	+70	+90	+120
Thrust, Ignition, lbf	2406	2478	2570	2671	2750	2880
Thrust, Maximum, lbf	2493	2571	2670	2775	2860	2997
Thrust, Average, lbf	2260	2330	2420	2491	2541	2618
Impulse, Total, lbf-sec	44367	44410	44455	44522	44569	44635
Propellant Specific Impulse, lbf-sec/lbm	289.2	289.5	289.8	290.2	290.5	291.0

5.0 BIBLIOGRAPHY

5.1 References

5.1.1 National Aeronautics and Space Administration, Goddard Space Flight Center, Specification for Apogee Kick Motor for Radio Astronomy Explorer, Spec. No. 67-58 Revision A, 29 September 1965 (&).

5.1.2 Evaluation of Two Radio Astronomy Explorer Spacecraft Kick Motors Tested in the Spin Mode at Simulated Altitude Conditioned AEDC-TR-67-127, July 1967.

5.1.3 Thiokol Chemical Corporation, Elkton Division, Computer Program, Evaluation of Throat and Surface Area Time Histories E-40286, 25 August, 1967.

5.1.4 Thiokol Chemical Corporation, Elkton Division, Computer Program, Internal Ballistic Analysis for Gas Generators, E-40305, 2 March 1967.

5.1.5 Thiokol Chemical Corporation, Elkton Division, Test Report for Six TE-P-386-6 Open Air Tests Using the TC-21 5 Amp, 5 Watt No Fire High Energy Squib, E19-66, 2 March 1966.

5.1.6 Thiokol Chemical Corporation, Elkton Division, Specification Ballistic Acceptance Procedure TE-M-364-2 Rocket Motor, P22006, 28 February 1966.

6.0 GLOSSARY

6.1 Definitions (The definitions used are taken from the CPIA Manual as directed by NASA Goddard.)

6.1.1 Temperature, Motor Conditioned, Firing. The motor conditioned firing temperature is the temperature which exists throughout the motor, particularly the propellant grain, at the time of firing.

6.1.2 Pressure, Chamber, Ignition, Maximum. The maximum ignition chamber pressure is the highest pressure recorded initially due to ignition.

6.1.3 Pressure, Chamber, Maximum. The maximum chamber pressure is the highest chamber pressure developed by the rocket motor under any normal operating condition exclusive of ignition.

6.1.4 Pressure, Chamber, Average. The average chamber pressure is the quotient of the burn time integral of chamber pressure divided by the burn time.

6.1.5 Time, Burn. Burn time is defined as beginning when the pressure has risen to 10 percent of its maximum value (exclusive of ignition) and as ending when the pressure begins to drop sharply near the end. The latter point is determined as follows: Tangents are drawn to the descending portion and to the level portion of the curve. The angle between the two tangents is bisected by a line extended to the curve. A line parallel to the pressure axis is drawn from the intersection of the bisection with the curve to the time axis and this point indicates the end of burning.

6.1.6 Time, Action. Action time is defined as the time between 10% of maximum pressure (exclusive of ignition) on the ascending and descending portions of the pressure-time curve.

6.1.7 Time, Operation. The operation time is defined as beginning at the first perceptible indication of pressure and ending when the pressure falls to zero.

6.1.8 Time, Zero. Zero time is the time at which firing voltage is applied to the igniter circuit.

6.1.9 Time, Ignition Delay. Ignition delay time is defined as beginning at zero time and ending when the pressure has risen to 10% of its maximum value (exclusive of ignition) on the ascending portion of pressure-time curve.

6.1.10 Time, Ignition Rise. Ignition rise time is defined as beginning when the pressure has risen to 10% of its maximum value on the ascending portion of the pressure-time curve and ending when the pressure has risen to 75% of its maximum value (exclusive of ignition) still on the ascending portion of the pressure-time curve.

6.1.11 Time, Ignition. The ignition time is defined as beginning at zero time and ending when the pressure has risen to 75% of its maximum value (exclusive of ignition) on the ascending portion of the pressure-time curve.

6.1.12 Thrust, Ignition, Maximum. The maximum ignition thrust is the highest thrust recorded initially due to ignition.

6.1.13 Thrust, Maximum. The maximum thrust is the highest thrust developed by the rocket motor under any normal operating condition exclusive of ignition.

6.1.14 Thrust, Average. The average thrust is the quotient of burn time impulse divided by the burn time.

6.1.15 Impulse, Specific, Propellant. The propellant specific impulse is the quotient of the total impulse divided by the total weight of propellant burned, including PYROGEN propellant.

6.1.16 Impulse, Total. The total impulse is the integral of the thrust over the operation of the motor.

7.0 APPENDIX

7.1 Propellant Burning Surface Area-VS-Percent Web

Percent Web	Surface Area (in^2)	Throat Area (in^2)
0.000	426.50	1.478
0.01	432.48	1.366
1.740	435.10	1.413
4.060	420.90	1.471
10.400	429.10	1.486
20.300	423.20	1.505
26.200	418.60	1.522
32.000	427.50	1.542
40.700	455.60	1.582
49.400	479.90	1.620
61.000	500.90	1.679
69.800	505.60	1.728
78.500	492.00	1.768
90.100	452.80	1.810
100.000	386.00	1.835
102.000	274.40	1.835
103.700	102.90	1.835
107.500	0.00	1.835

7.2 Propellant Ballistic Properties (Obtained in the Ballistic Data Fit)

Burn rate, in/sec = 0.307 $(P_c/830)^{0.29}$ where P_c = Chamber Pressure, psia at 90°F

Density, lbm/cu. in. = 0.06278

Pressure Coefficient of Temperature, π_k, %/°F = 0.154

Ratio, Specific Heats = 1.16

C_d = .976 C* = 4959.5 @ 90°F

7.3 Single PYROGEN OPEN AIR IGNITER PERFORMANCE

C* (ft/sec)	Burn Rate Exponent	Gamma	Propellant Weight (lbm)	Temperature (deg F)
4700.00	0.280	1.230	0.1412	70.0

Time (sec)	Pressure (psia)	Mass Flow (lbm/sec)
0.0050	2000.0	.34
0.0150	2240.0	.38
0.0480	1940.0	.33
0.0750	1960.0	.333
0.1000	1940.0	.33
0.1950	1680.0	.286
0.2080	1660.0	.282
0.2150	1500.0	.25
0.2250	400.0	.068
0.2380	60.0	.010
0.2750	0.0	.000

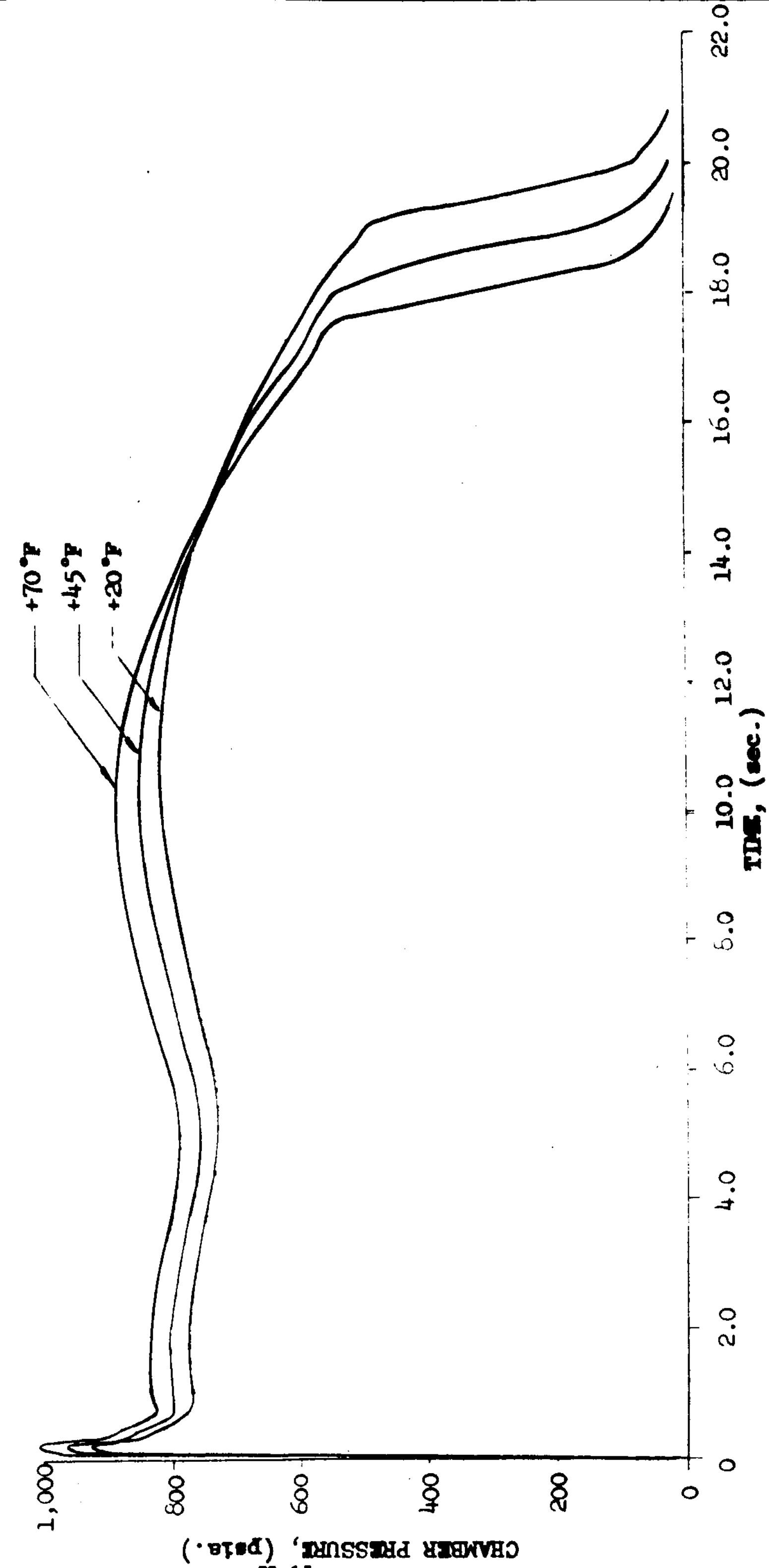


FIGURE 1. CALCULATED BALLISTIC PERFORMANCE, CHAMBER PRESSURE VS TIME

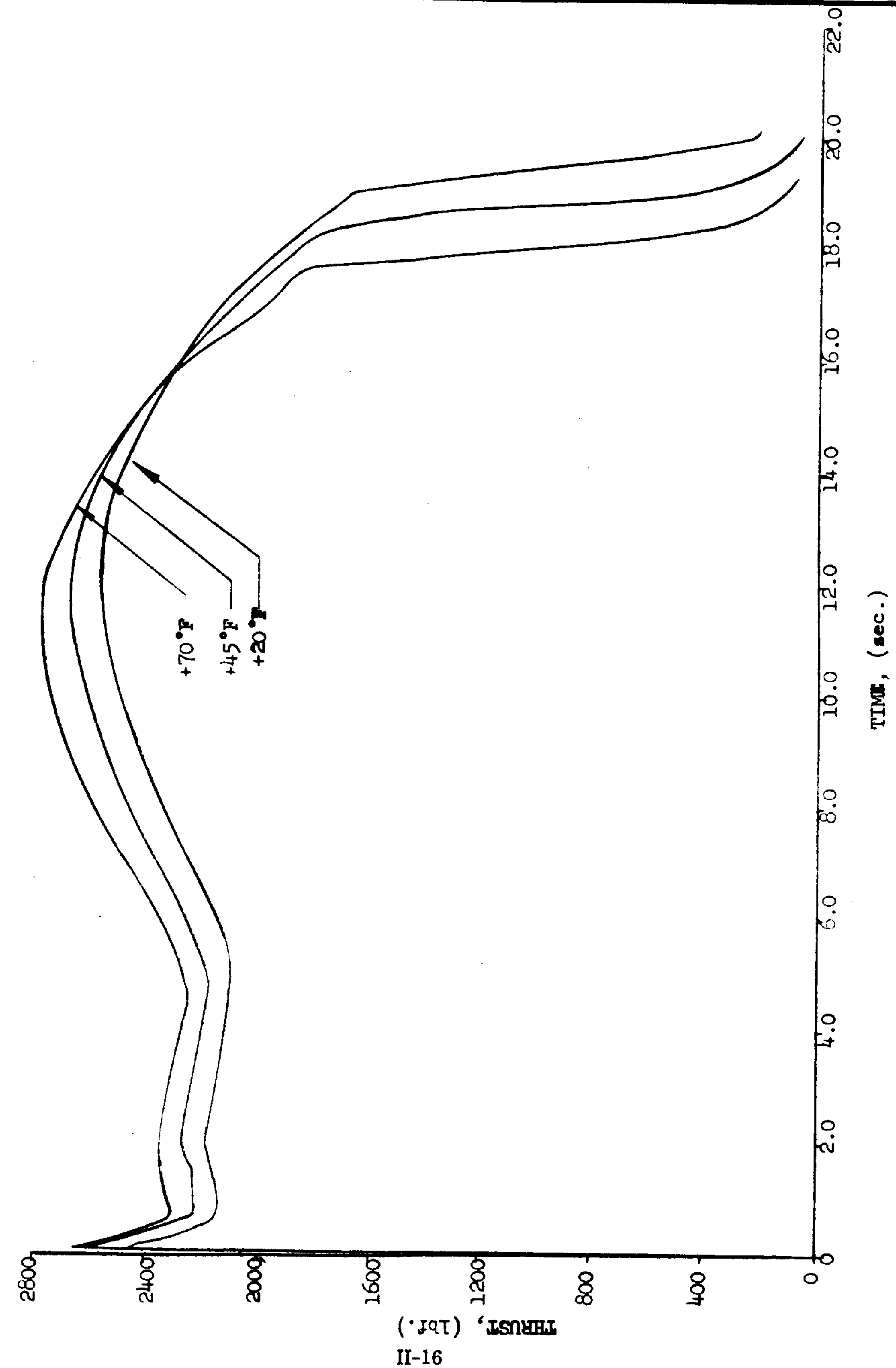


FIGURE 2. CALCULATED BALLISTIC PERFORMANCE, VACUUM THRUST VS TIME

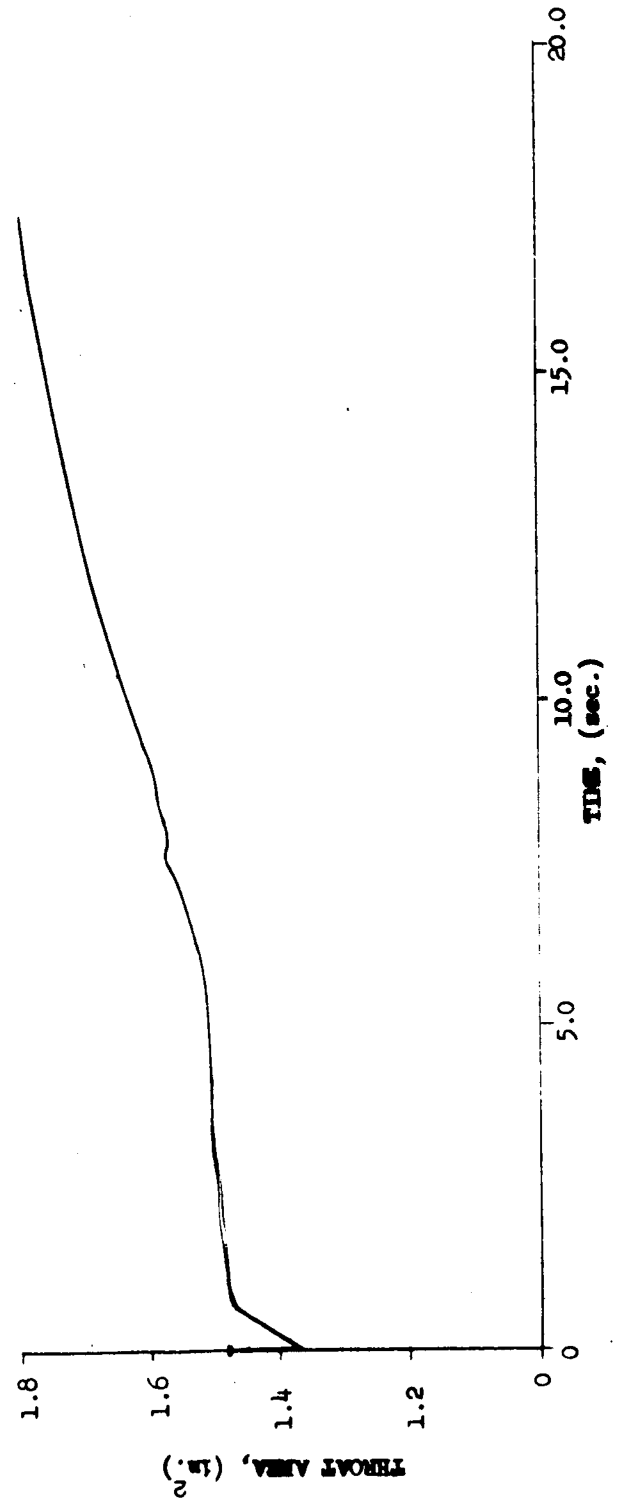


FIGURE 3. THROAT AREA VS TIME - MOTOR PV16-659-7

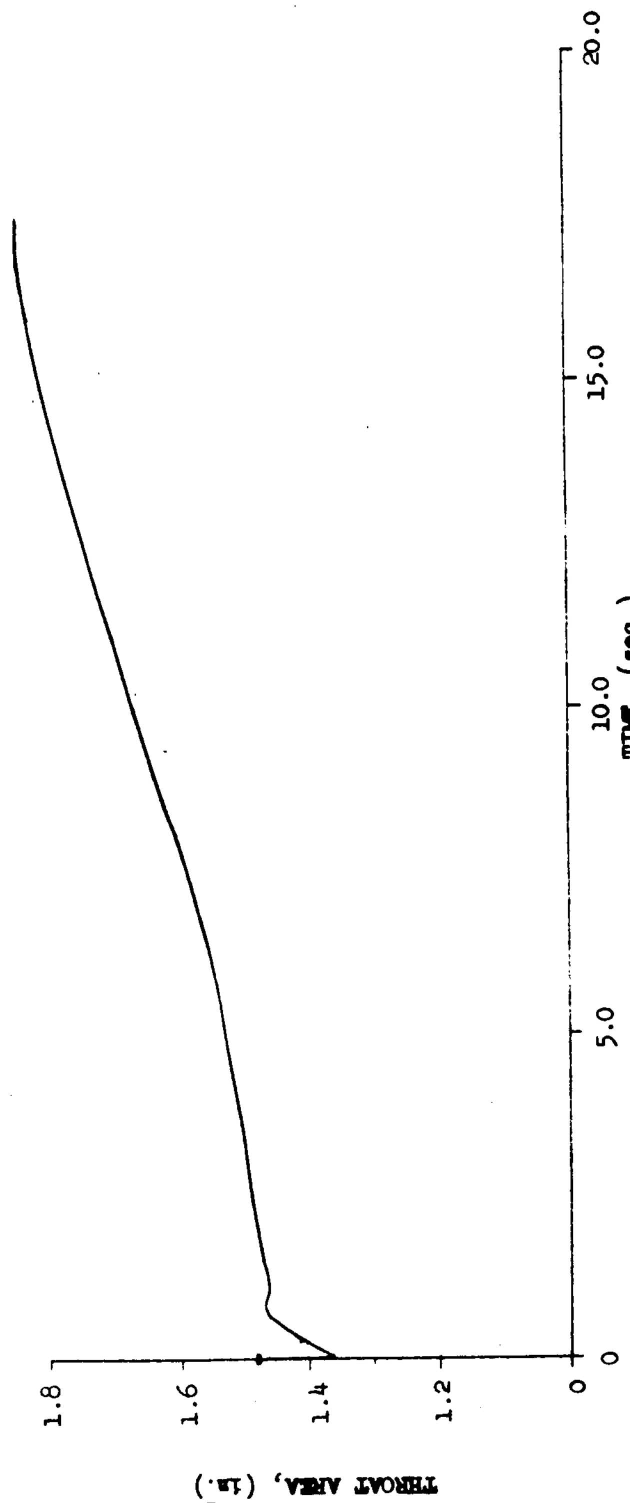


FIGURE 4. THROAT AREA VS TIME - MOTOR PV16-659-10

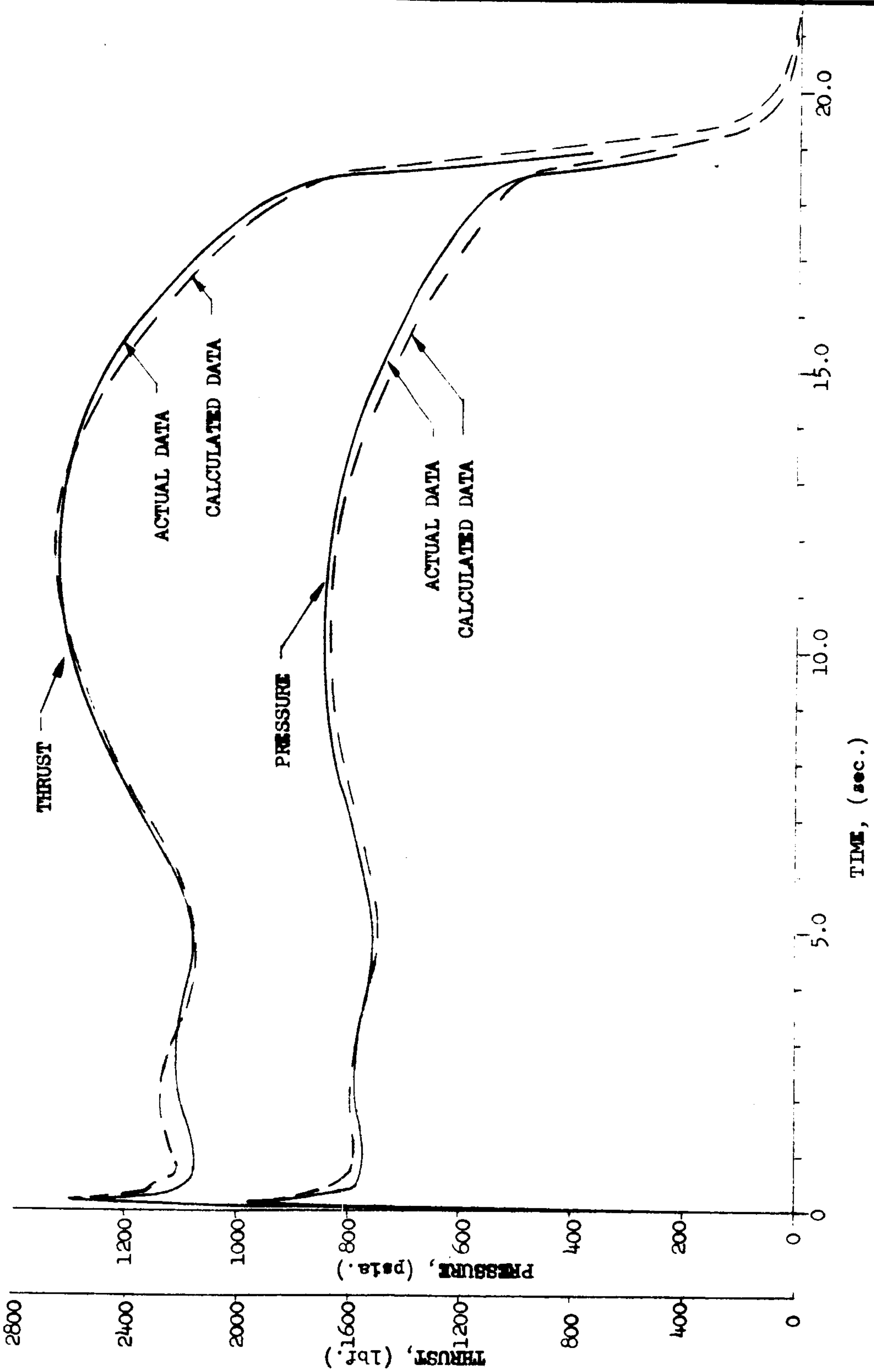


FIGURE 5. BALLISTIC PERFORMANCE - MOTOR PV16-659-7

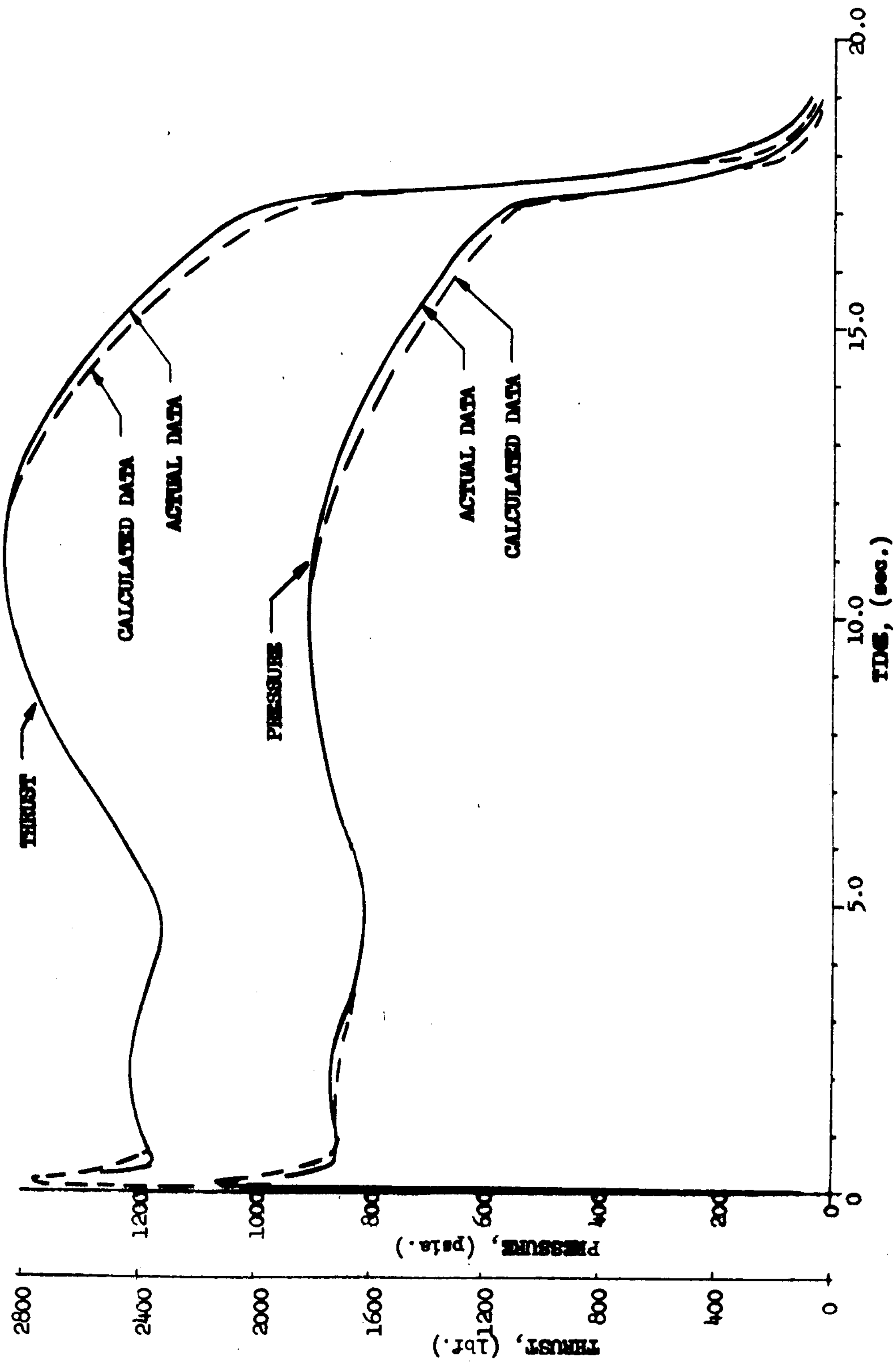


FIGURE 6. BALLISTIC PERFORMANCE - MOTOR PV16-659-10

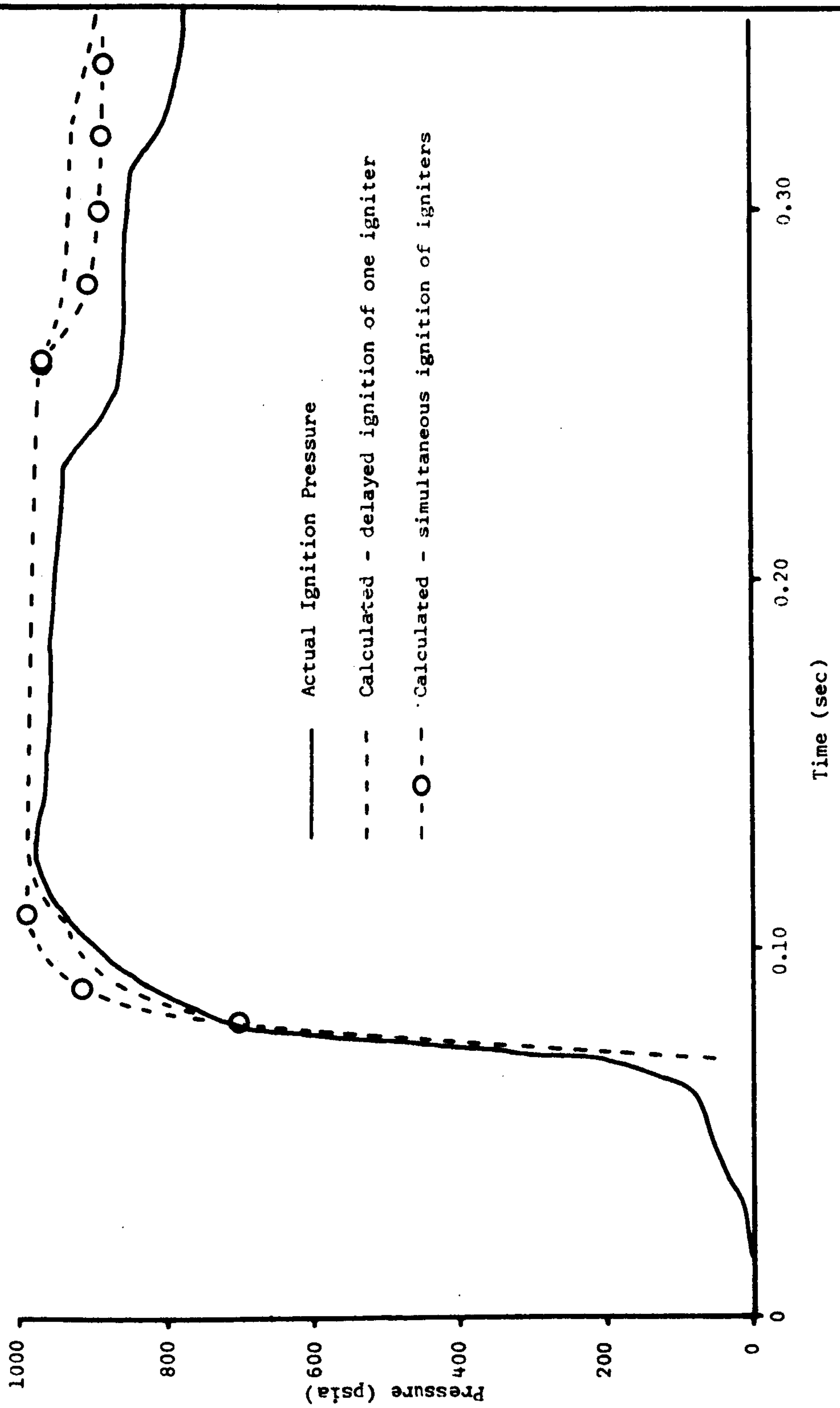


FIGURE 7. IGNITION PRESSURE VS TIME - MOTOR PV16-659-7

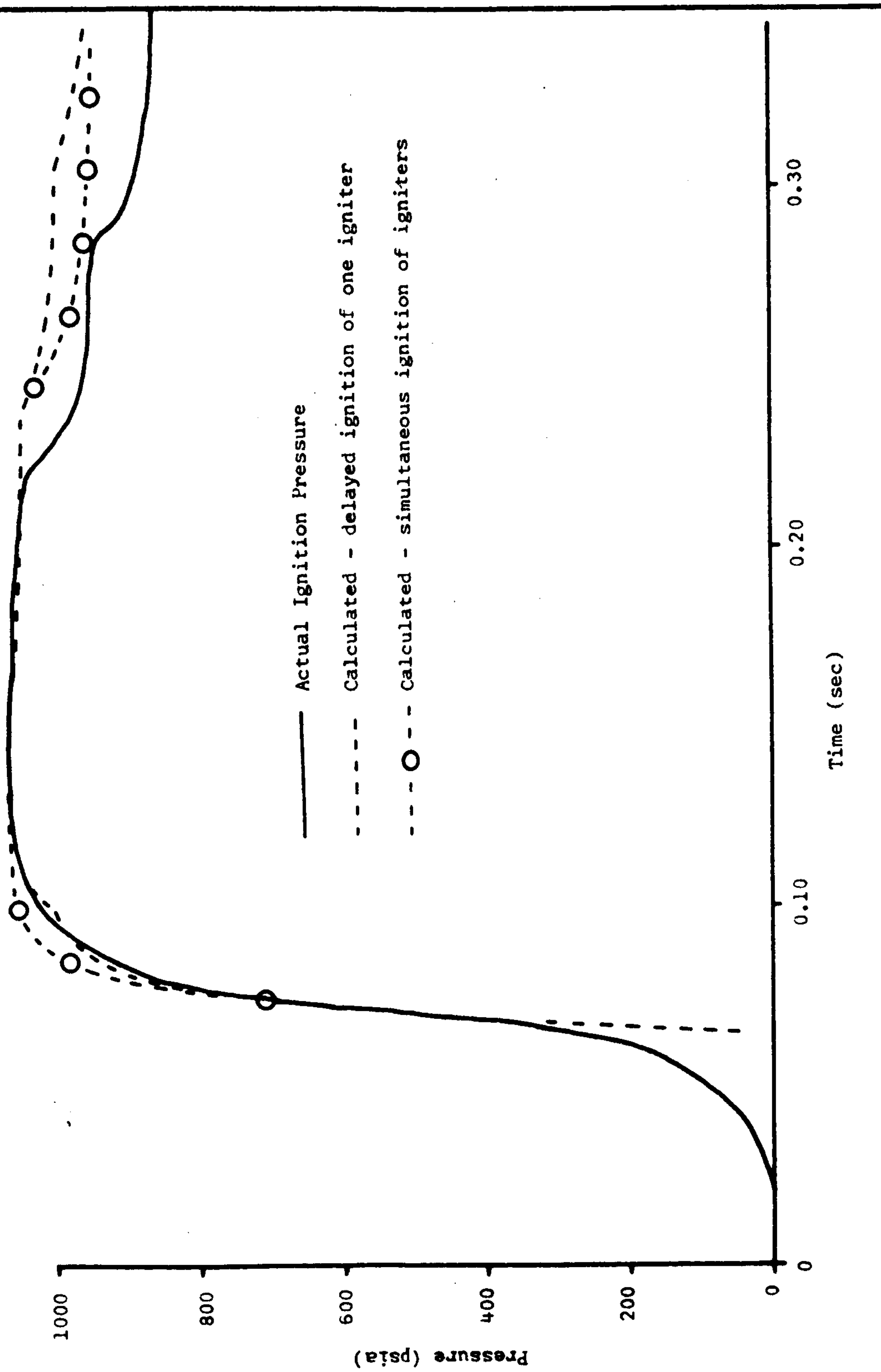
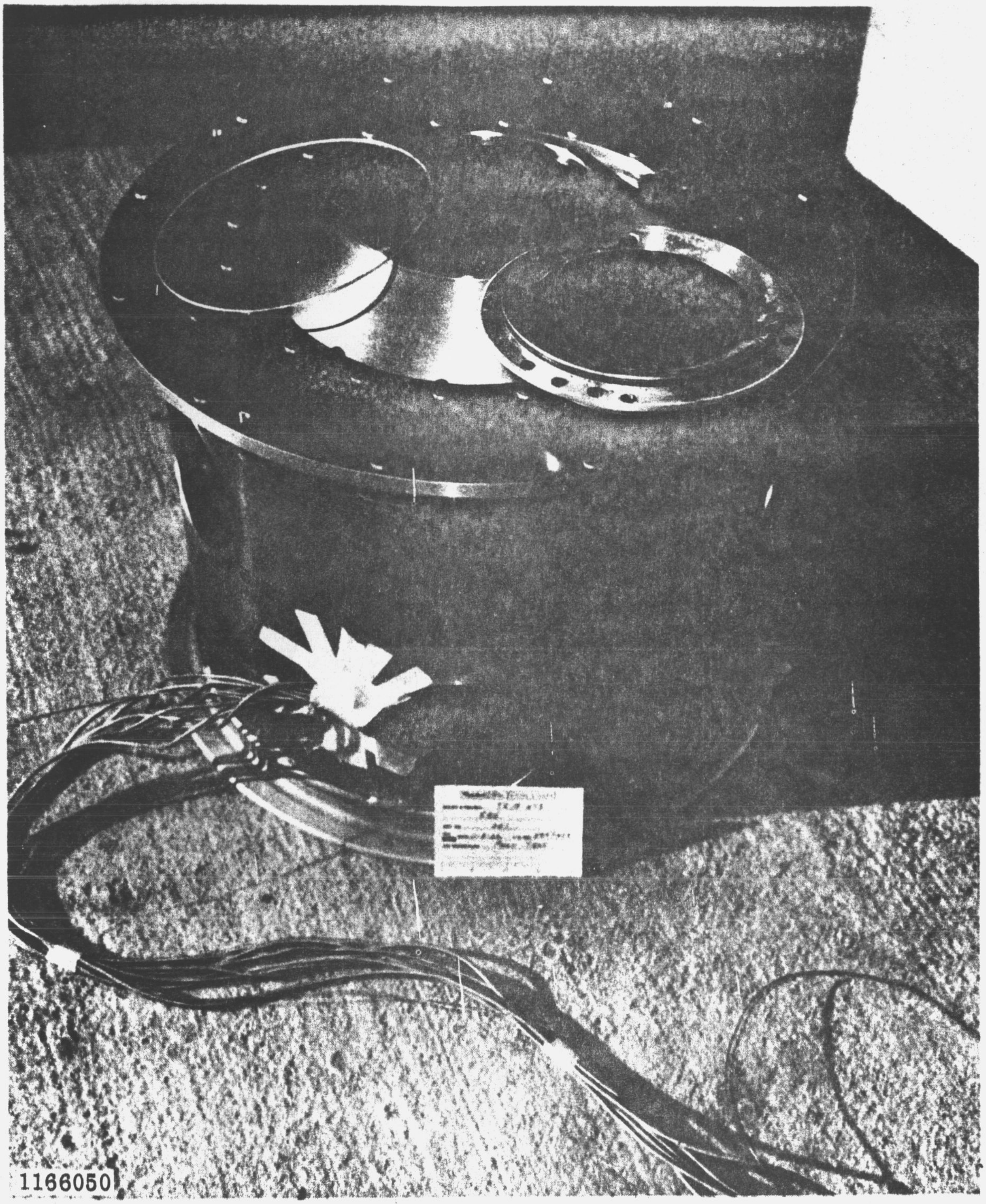


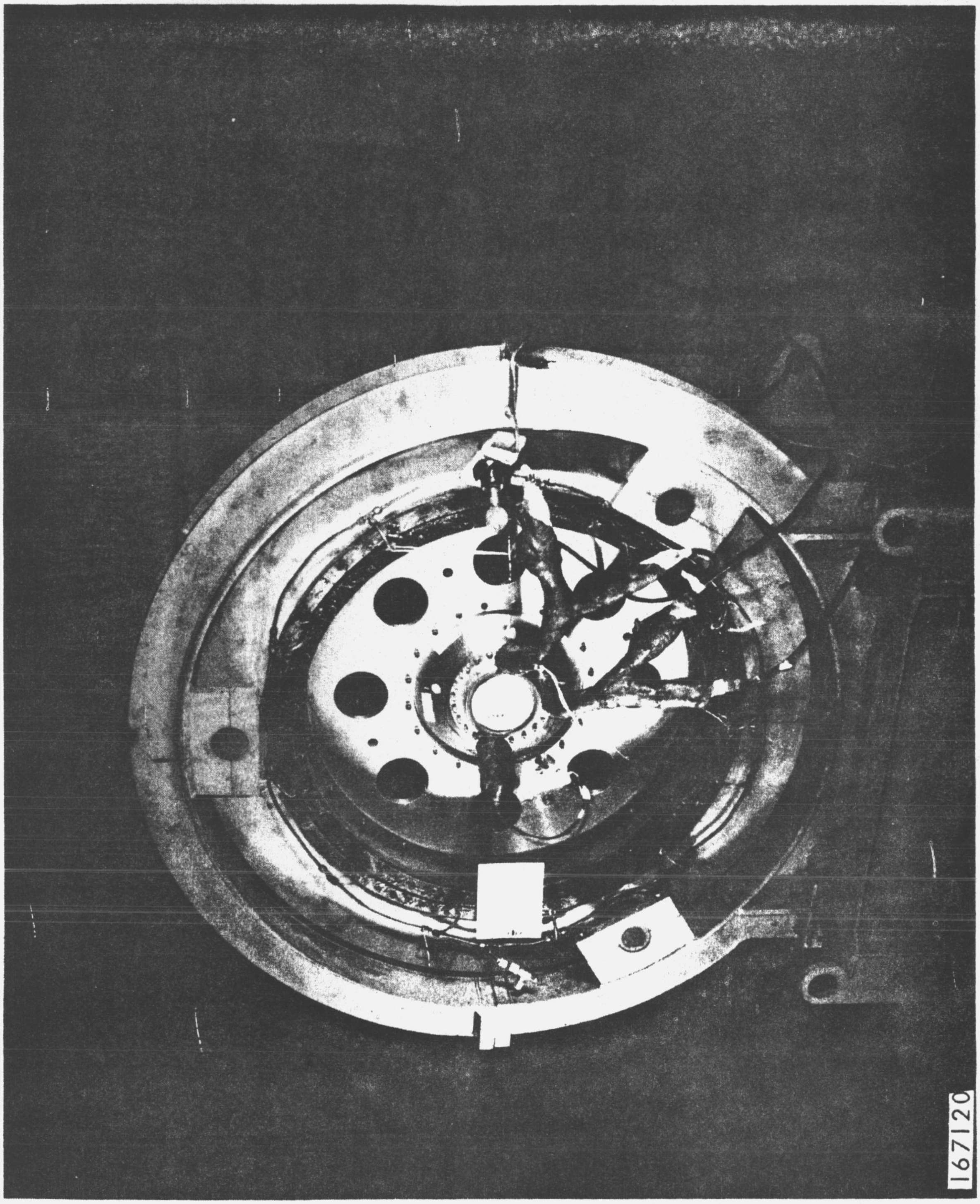
FIGURE 8. IGNITION PRESSURE VS TIME - MOTOR PV16-659-10

APPENDIX III

PRE- AND POST-TEST PHOTOGRAPHS



HYDROBURST TEST, POST-TEST



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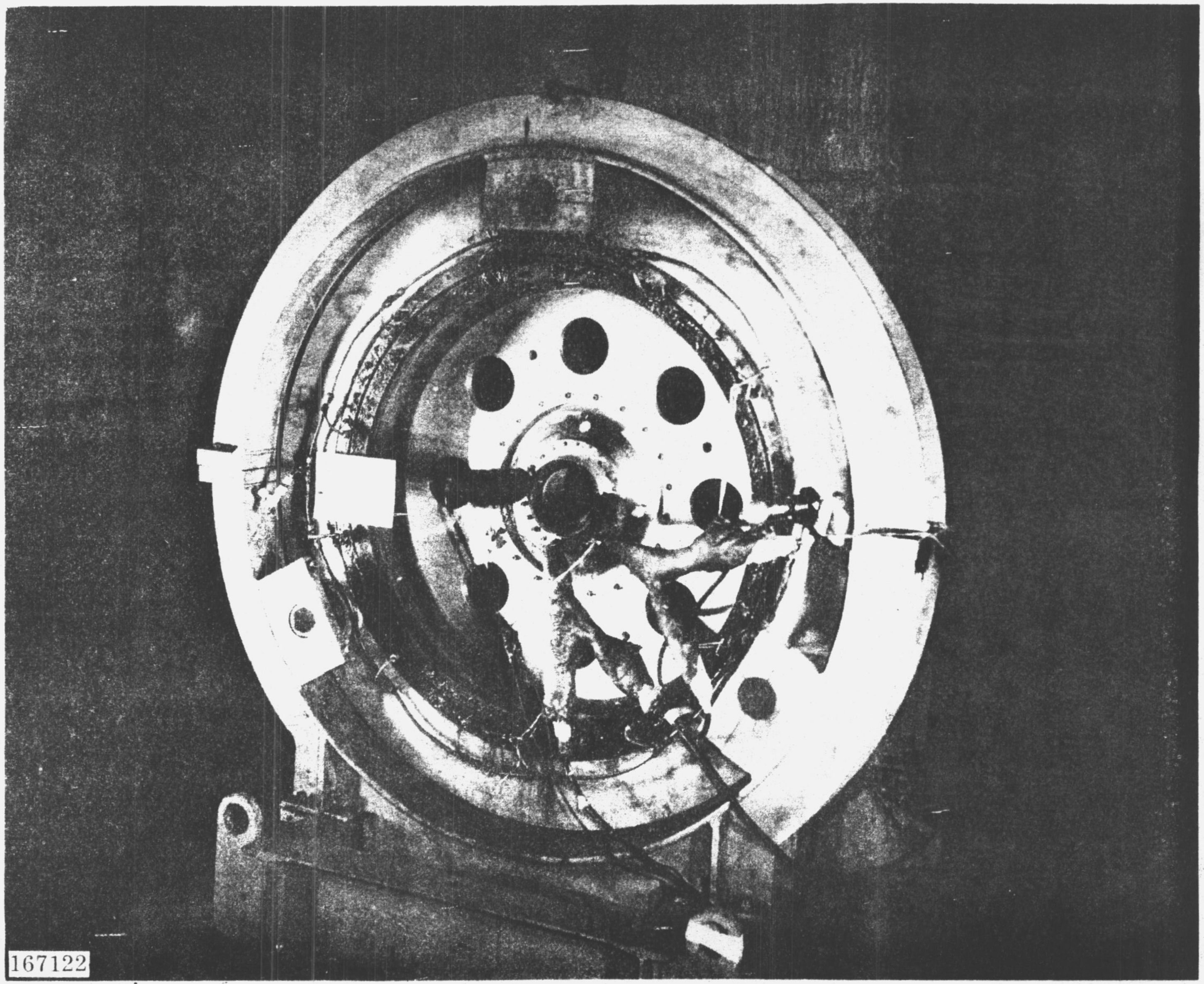

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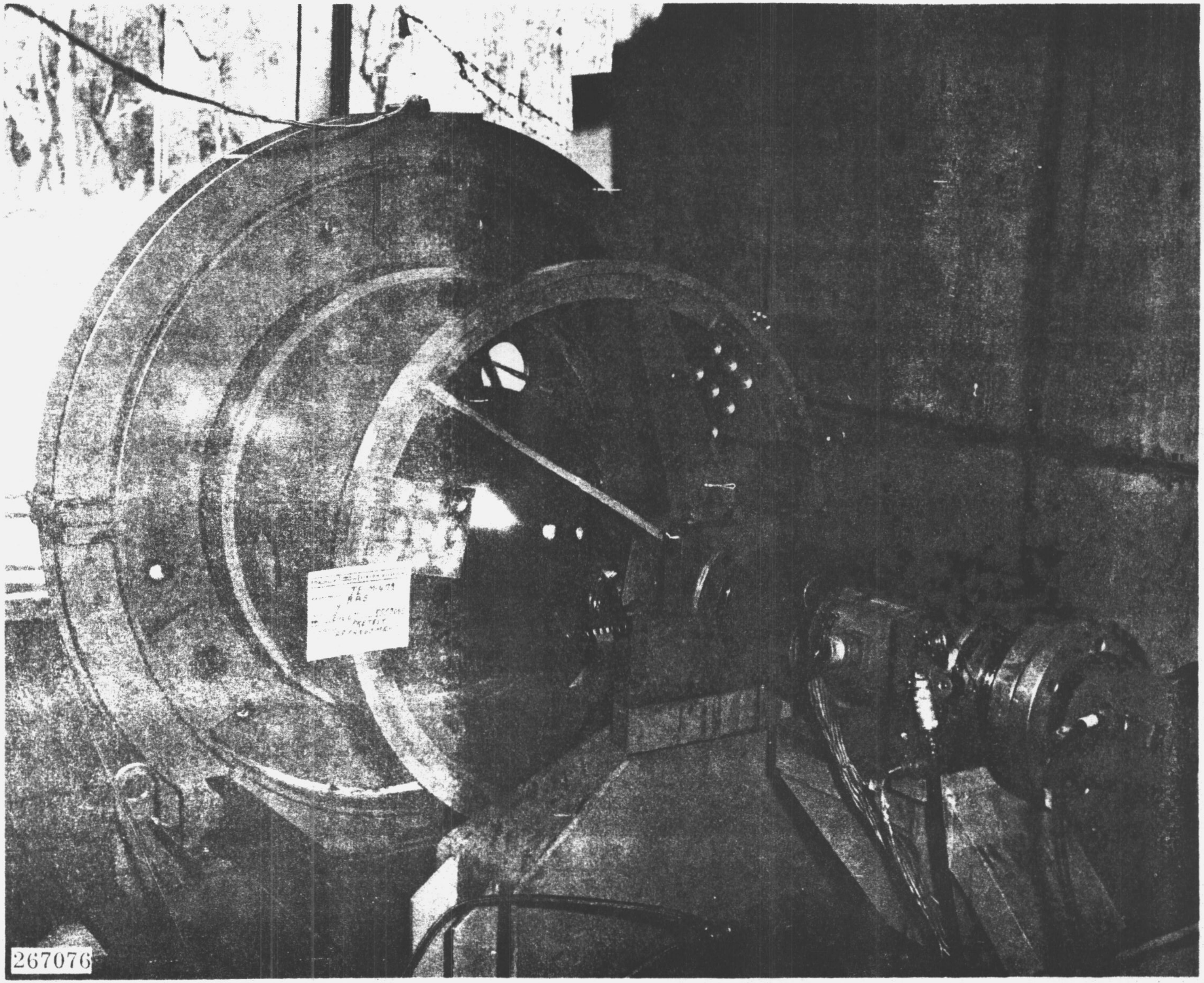

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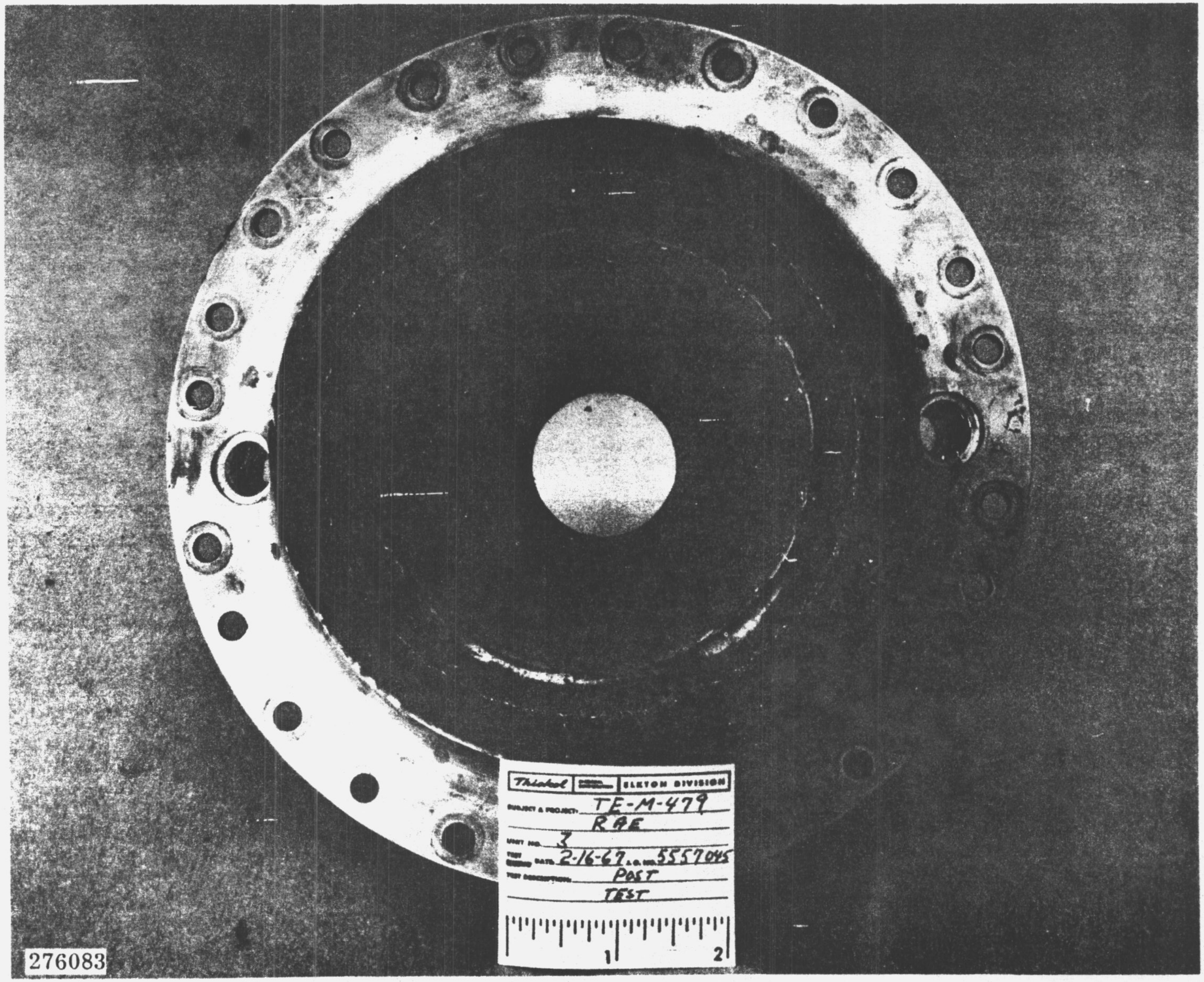
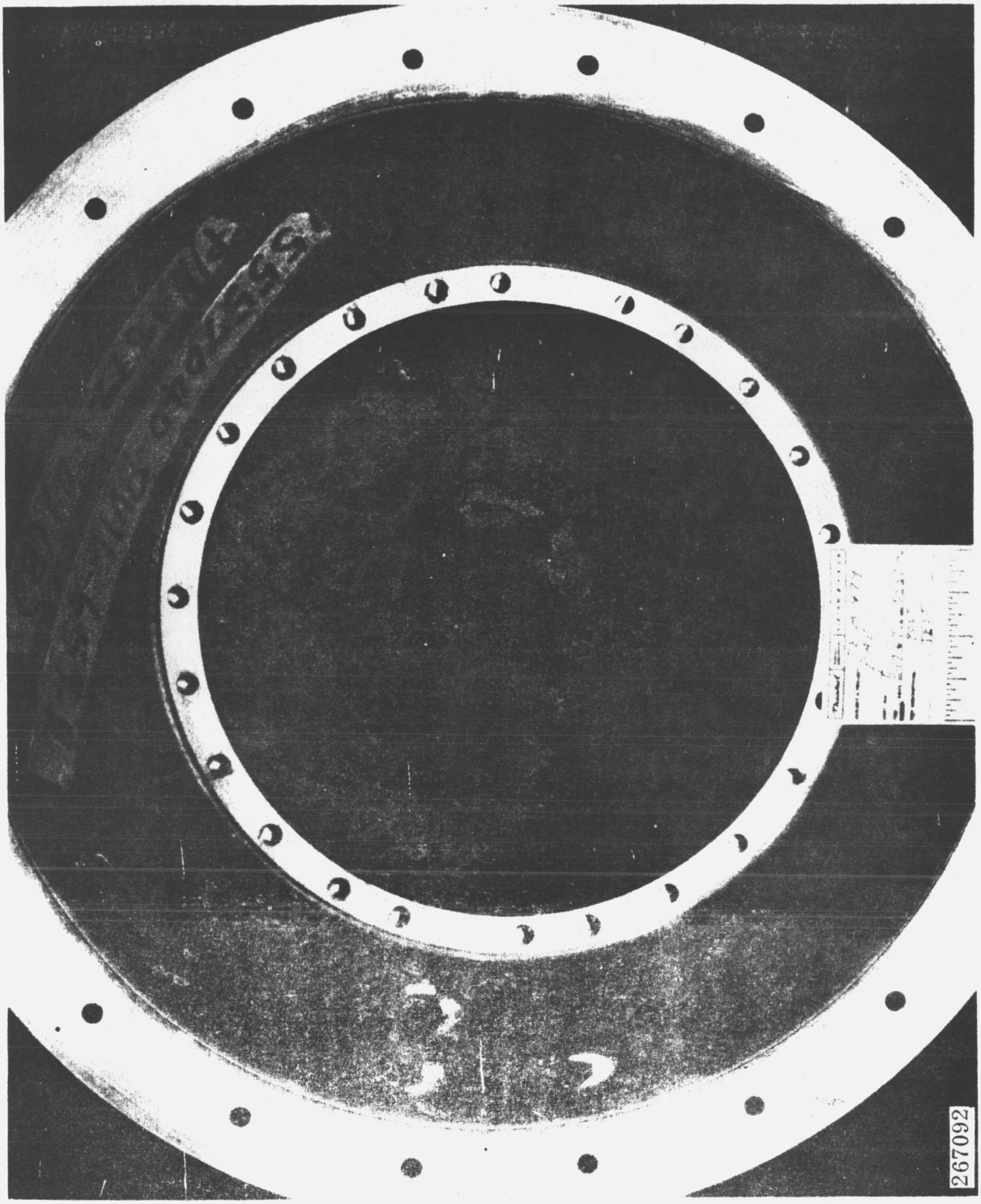


PV16-659-1, POST-TEST

267094

PV16-659-2 POST-TEST



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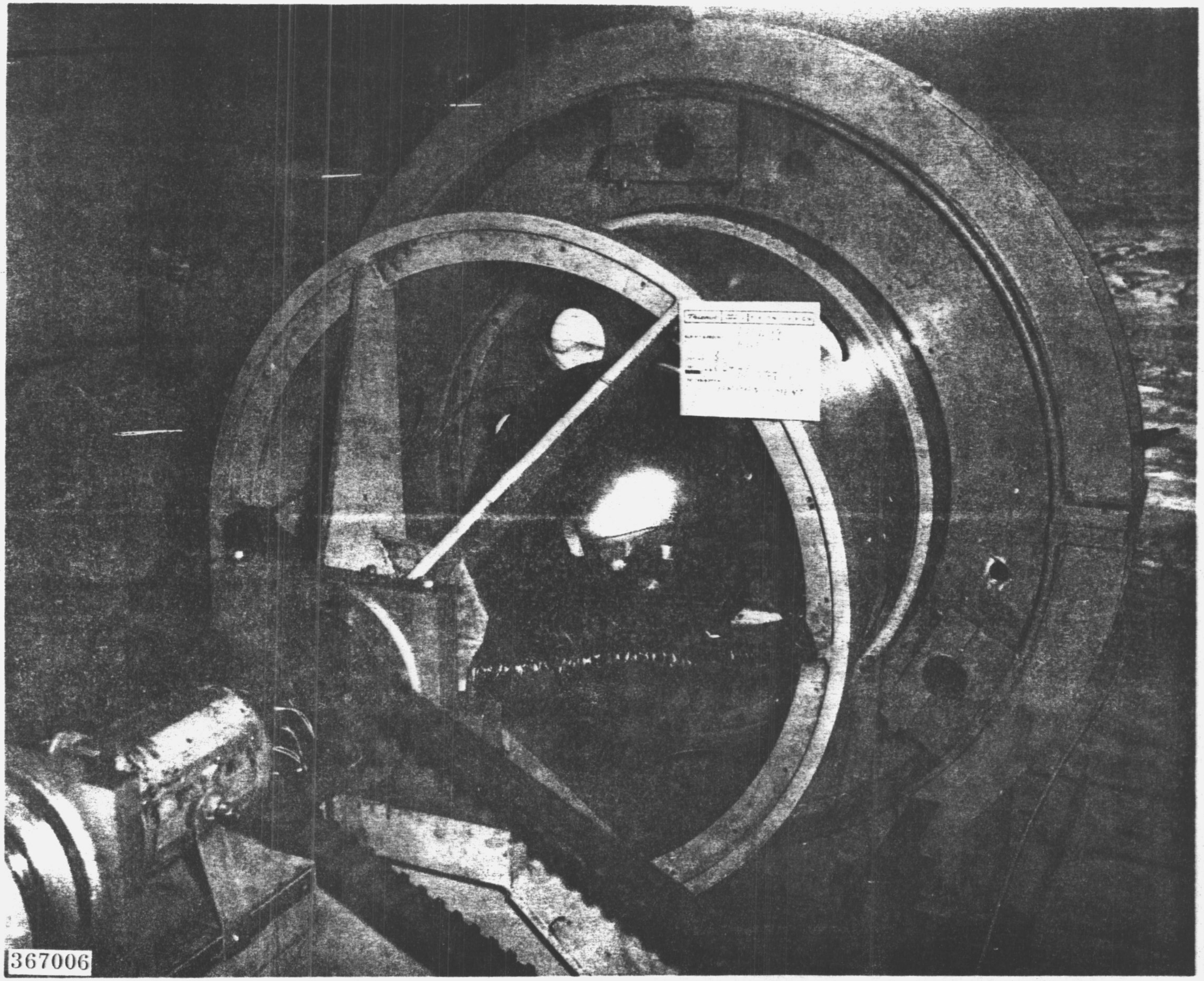

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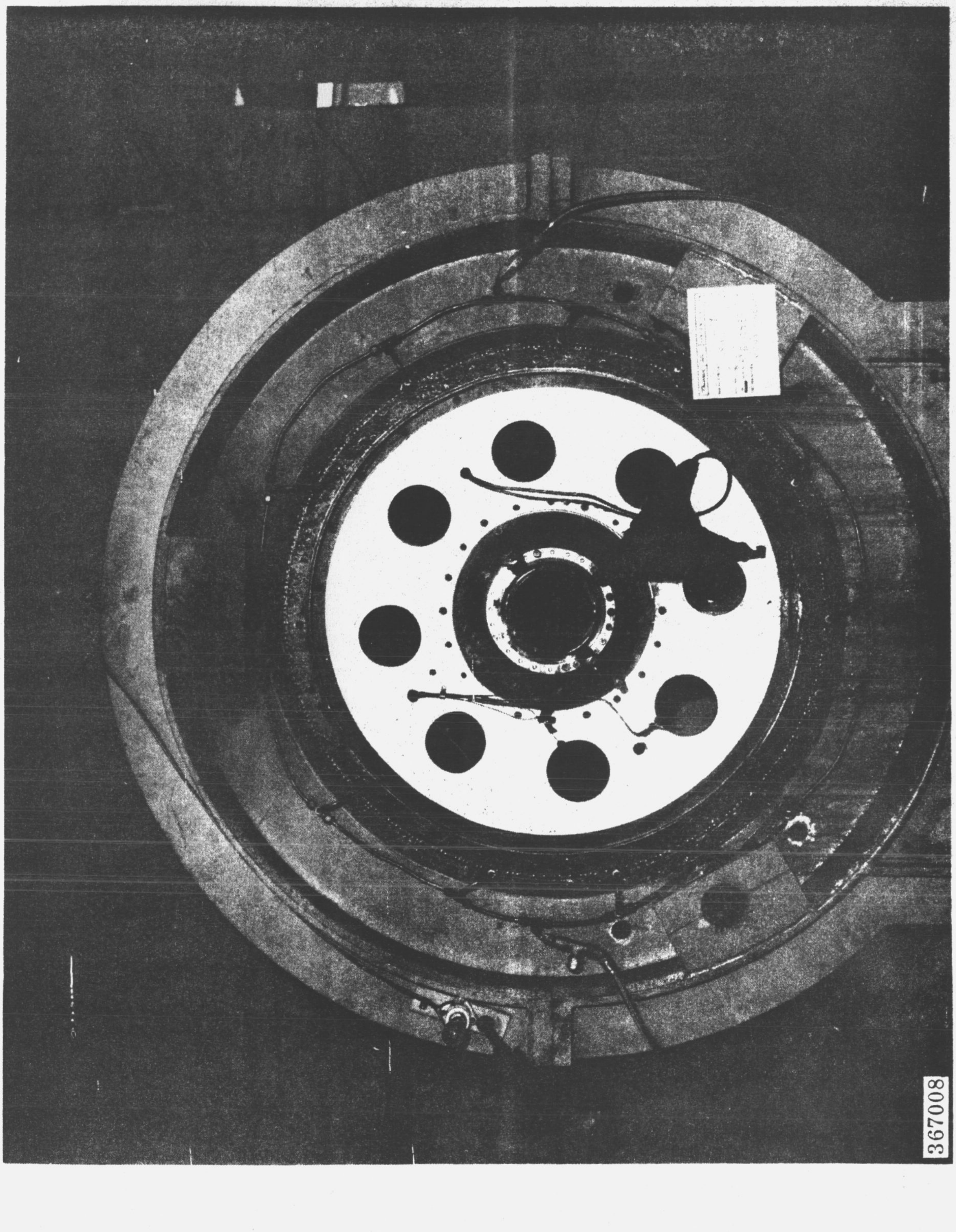

PV16-659-3, POST-TEST

N66 20197

Thiokol

CHEMICAL CORPORATION

ELKTON DIVISION

ELKTON, MARYLAND 21921

TELEPHONE 301-398-3000

TWX 301-398-3914

In Reply Refer To:
E75-68

March 6, 1968

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Subject: Errata - E75-68

Reference: E75-68, Final Report on Contract NAS5-9336, February 26, 1968

Gentlemen:

The subject report contained several errors. Please correct your copies of this report as follows:

Page	Reads	Please Change To
ii	Misalignment, degrees,[2]	Misalignment,[2]
-1-	one-amp/one watt ( )	one-amp/one watt. no-fire ( )
-1-	0.038 ± 0.006 inch	0.038 + 0.006 inch
-3-	1A/1W initiator (twice)	1A/1W no-fire initiator
-8-	...to NASA in...	To NASA for their consideration in...
-21-	Appendix B	Appendix II
-21-	Appendix C	Appendix III
-21-	+ 62 - 92	+ 62 - 111
I-1	I_{sp} (col. Heading) lbf-sec	I_{sp} sec
I-1	I_{tot} (col. Heading) sec	I_{tot} lbf-sec

We regret any inconvenience this may have caused.

Very truly yours,

THIOKOL CHEMICAL CORPORATION
ELKTON DIVISION

Edward F. Colburn

E. F. Colburn
Program Manager

JGEarly/mp